Ecological Crop Geography

THE MACMILLAN COMPANY
NEW YORK · BOSTON · CHICAGO · DALLAS
ATLANTA · SAN FRANCISCO

MACMILLAN AND CO., LIMITED
LONDON · BOMBAY · CALCUTTA · MADRAS
MELBOURNE

THE MACMILLAN COMPANY
OF CANADA, LIMITED
TORONTO

ECOLOGICAL CROP GEOGRAPHY

BY *Karl H. W. Klages* PROFESSOR OF AGRONOMY, UNIVERSITY OF IDAHO, AND AGRONOMIST, IDAHO AGRICULTURAL EXPERIMENT STATION

NEW YORK · 1949

The Macmillan Company

Printed in the United States of America.

Published May, 1942.
Reprinted September, 1947;
February, 1949.

TO MY
FATHER AND MOTHER

PREFACE

This book is a direct outgrowth of a course in Crop Ecology offered by Dr. W. L. Burlison of the University of Illinois, and taken by the author as a graduate student in 1921–22. It was under the guidance of Dr. Burlison that the author received his original inspiration to pursue the many interesting possibilities of the ecological phases of crop production and distribution. No small amount of credit for the development of this book is therefore due to my former teacher. Dr. Burlison accomplished one of the great realizations of a teacher in that he created in his student a definite interest in a subject, implanted a new trend of thought, and imbued him with a desire to pursue a line of study started in the classroom.

It has been the good fortune of the author to have had the opportunity to carry on this line of study in a number of institutions in widely separated agricultural areas in the United States, as at the Colorado Agricultural College, at the Oklahoma Agricultural and Mechanical College, at the South Dakota State College, and of late in the University of Idaho. The reactions of the author's students to the subject matter presented in this book have played an important part in its development and in its appearance in final form. The materials covered in this book have with modifications been presented to Agronomy students over a period of eighteen years.

In 1928 the author published a paper in the *Journal of the American Society of Agronomy* setting forth the place that may be occupied by a course in Crop Ecology and Ecological Crop Geography. The favorable response of many Agronomists to this paper offered a further stimulation to the compilation of a more comprehensive outline and to the eventual working over of the materials of the outline into book form.

The title of the book was originally designated as *Crop Ecology*. Since, however, the subject materials cover a very broad field

dealing not only with the ecological aspects but also with the more general factors determining, or involved in, the distribution of crops, the present title, *Ecological Crop Geography*, was deemed more appropriate. Credit for suggesting this particular title is due to Dr. C. R. Ball of the United States Department of Agriculture, who proposed it in connection with the review of the paper in the *Journal of the American Society of Agronomy* referred to above.

The book is divided into four parts. Part I treats the social environment. Part II gives a generalized discussion of the physiological environment. Part III deals with the separate ecological factors. These three parts provide the background for the discussion pertaining to the distribution of agronomically important crops in Part IV.

Part I develops the concept of the social environment of crop plants. In order to keep this volume within the desired size limitations, the factors of the social environment are intentionally discussed in a summary fashion. It is fully recognized that this phase of the subject may be enlarged upon considerably. But, it is also recognized that further elaboration on this important and often neglected phase of the study of crop distribution is best left as a task for Economists rather than to a writer with an Agronomic background. Since, however, the field of crop production, and especially as it relates to the distribution of crop plants, is so intimately related to economic, political, social, technological and historical forces, it is essential that the student of Agronomy be given an opportunity to consider these factors and their numerous interrelationships in their effects on world crop distribution.

Part II deals with the general aspects of the physiological environment. It has been the author's experience that a better perspective of the many and complex interactions of the plant with the factors of its environment can be given to students by first considering these interactions in their general aspects before taking up the more precise analysis of the environmental factors.

The detailed discussion of the factors of the physiological environment and the responses of plants to these various stimuli is presented in Part III. These ecological factors produce not only local but also regional responses. In view of this, and again in order to give the student a more complete outlook of world crop distribution, one chapter was devoted to the classification of climates. This

particular chapter was written with considerable hesitancy, even though no original classification was added to the many now in existence. While all the present available classifications of climate have been severely criticized, it can nevertheless not be denied that such classifications serve to identify and show relationships. They can be used to advantage by students of crop distribution when applied with a recognition of their definite limitations.

Part IV treats the actual distribution of crop plants. In this emphasis is given to the physiological growth requirements of the crop plants discussed, rather than to the statistical phases of the subject. In other words, while crop statistics are important in that they provide basic information, it is assumed that the reader is interested more in crop adaptations, the epharmony of crop plants, than in crop statistics as such. It is exactly in this feature, and in that the distribution of crop plants is discussed primarily on a physiological basis, that this book differs from the now available works dealing with the distribution of the World's agricultural resources.

The statistical data used were obtained from the *United States Department of Agriculture*, *Agricultural Statistics*, 1940. Some difficulty was encountered in the tabulation of the crops produced in the European countries for the obvious reason that the national boundaries of that continent are at the present writing undergoing rapid change. Yet, while the boundaries of the countries now engaged in the conflict will be altered, the land areas involved with their potentialities for production will remain, even though the social environments will undergo change.

The author has drawn freely on the available literature relating to the various phases of the topics presented. No claim is made for the complete exhaustion of the available literature, and no doubt many contributions of distinct value and with a direct bearing on the subject in hand have not been included in the discussions presented. The great breadth of the field of Ecological Crop Geography makes it impossible or impracticable to review in one limited volume all the numerous contributions having a direct bearing on the subject. Free use has also been made of crop distribution maps from the various publications of the United States Department of Agriculture.

The author is indebted to Professor G. O. Baker, Soil Tech-

nologist of the Idaho Agricultural Experiment Station, for checking the chapter on Edaphic and Physiographic Factors.

The author wishes to express his appreciation for the helpful suggestions of the Editorial Staff of The Macmillan Company in the preparation of the materials for publication.

This book represents a first attempt to place the many problems incident to the distribution of crop plants on a physiological basis. It is written to fill a long-felt need by Agronomists, Economists, Geographers, and other workers. While this volume covers a wide field it is fully realized that the study presented is by no means complete. Many of the subject matter problems touched upon are awaiting elaboration and solution. It is the sincere hope of the author that this book may serve to encourage other investigators to initiate and complete projects leading to a more comprehensive understanding of the problems of crop distribution, to a wiser and more beneficial use of the products of the soil, and to the conservation of the agricultural resources of the United States and of the World.

K. H. W. K.

UNIVERSITY OF IDAHO
Moscow
March, 1942

CONTENTS

PART I. THE SOCIAL ENVIRONMENT OF CROP PLANTS

PART III. THE ECOLOGICAL FACTORS

PART I

THE SOCIAL ENVIRONMENT OF CROP PLANTS

Chapter I

THE SCOPE OF ECOLOGICAL CROP GEOGRAPHY

Crop Ecology and Ecological Crop Geography and Studies in Agronomy and Agronomic Investigations. Ball (2) very ably defines agronomy as the "art and science of field crop culture." He enlarges on this definition by continuing that agronomy "more specifically is the art and underlying science of so handling the crop plant and the soil substrate as to produce the highest possible quantity and quality of the desired crop product from each unit of land and soil and water and light, with a minimum of immediate or future expense in labor and soil fertility." In standard dictionaries agronomy is generally defined as "the management of land" and as "rural economy." The general public has learned that the term applies to the study of problems connected with the production of farm crops.

Two facts are in evidence from the attempts of defining agronomy; (*a*) the physiological and (*b*) the economic relationships. The present divisions of agronomic studies are in themselves indicative of the far-reaching activities in this general field of agricultural research. The main lines are generally drawn along crops and soils studies. These divisions are subdivided into special phases even though the lines between crops and soils studies may not always be definite. Plants grow in the soil, and results of soil treatment are generally measured by plant responses.

Developments, especially in recent years, have brought out forcefully the necessity for what may be termed a world outlook on agricultural production. Agricultural production, or any other form of production, is influenced not only by local but to a great extent by world conditions. The development of such a conception of agricultural production demands a broad outlook; it cannot confine itself to the physiological and mechanical phases of production in any one locality but must consider also the world economic and social forces influencing production of specified crop plants.

It is essential for the agronomist, in order to obtain a well-rounded concept of his field, not only to consider local factors of production but also to become acquainted with the main factors determining the location of centers of crop production within the confines of his own country and with those forces determining world centers of production. Jevons, the English economist, summed up the condition in an admirable fashion when as early as 1865 he wrote the following:

> "The plains of North America and Russia are our corn fields; Chicago and Odessa our granaries; Canada and the Baltic are our timber-forests; Australia contains our sheep farms; and in Argentina and on the western prairies of North America are our herds of oxen; Peru sends her silver, and the gold of South Africa and Australia flows to London; the Hindus and the Chinese grow tea for us, and our sugar and spice plantations are in all the Indies. Spain and France are our vineyards, and the Mediterranean our fruit garden; and our cotton grounds, which for long have occupied the southern United States, are now being extended everywhere in the warm regions of the earth."

Klages (11) discussed in detail the place that may be given to crop ecology and ecological crop geography in the agronomic curriculum.

Ecology. The word "ecology" is derived from the Greek "oikos" meaning house, abode, or dwelling. The term, according to Hansen (8), was first introduced by E. Haeckel. Tansley (15) used the term in its "widest meaning" as the study of organisms as they exist in their natural homes; or as the economy, household affairs, of organisms. Adaptations to external conditions may be designated as ecological; or, as Warming (16) terms it, adaptation involves detailed studies in ecological relationships.

Investigations during the past half century have set ecology and ecological relationships more and more on a scientific and, it may be said, an experimental basis. To explain how organisms adapt themselves to a precise environment calls for a mustering of all available knowledge of plant morphology, anatomy, and physiology. It is not too inclusive to say that most agronomic investigations touch very directly on the ecological relationships of crop plants. Soil investigations, work in crop breeding, variety testing, choice of special crops to meet certain conditions, and numerous other agronomic projects are definitely based on ecology and ecological relationships.

Plant Ecology. Plant ecology deals with plants in relation to their environments. Since the herbivorous animals obtain their sustenance from plant life, it is not always possible or desirable to divorce plant and animal ecology (Hesse, 9). The plant ecologist is concerned mainly with the habitats of plants and associations of plants or with the physiology of the plant or group of plants in a particular environment.

Crop Ecology. On first consideration it may seem hardly necessary to set up a separate definition for crop ecology as differentiated from plant ecology except to limit and to outline more definitely the scope of each. Crop ecology may be defined as the ecology of crop plants. In order to avoid confusion between the tasks of crop ecology and ecological crop geography, the study of the former should be confined to investigations of the relationships of crop plants to their physiological environments to the exclusion of the economic factors encountered in the production and distribution of a crop or group of crops. The effects of both the physiological and economic factors on production and distribution of crops will be treated under the more comprehensive and general field of ecological crop geography.

Ecological Crop Geography. Ecological crop geography[1] deals with the broad distribution of crop plants and with the underlying reasons for such distributions. The ecological crop geographer is concerned with more than the direct relationships of crop plants to their physiological environment. He must consider the points taken into account by the crop ecologist and in addition must recognize the operation of economic, political, historical, technological, and social forces. These additional forces are grouped under the general term "social environment." Thus, ecological crop geography may be defined as the study of crop plants in relation to their physiological and social environments. It is sufficient to state that the main ecological factors such as water relationships, temperature relationships, light relationships, and the form and availability of plant nutrients determine the physiological limits of crop production. All these factors not only are necessary for the normal development of plants but must again be taken into consideration

[1] The author is indebted to Dr. C. R. Ball of the United States Department of Agriculture for the suggestion to differentiate between crop ecology and ecological crop geography. Originally he defined crop ecology by the definition now given to ecological crop geography.

in the studies of abnormal manifestations of plant life. Plant pathologists are aware of the fact that disorders in plants, be they physiogenic or parasitic in nature, are either augmented or decreased in their severity by the influence of the environmental factors. Entomologists find a similar connection between the development and relative abundance of plant pests and these same factors.

Centers of crop production are determined in part by economic forces such as demand, facilities for handling the crop, costs of transportation, various labor problems, and competition. For instance, there is a close correlation between the centers of potato production and world centers of population, more especially centers of the white population. Comparatively nonperishable crops are often grown at considerable distances from such centers of population. In many instances an improvement in the prevailing systems of transportation may throw two rather remote sections into active competition.

The westward movement of agricultural production in the United States during the last century was influenced by a great variety of ecological, social, and economic factors. The fertility and ease with which the soils of the Mississippi Valley could be brought into production was the great magnet attracting settlers and prospective producers. Social and political circumstances immediately before and following the Civil War — notably the ease with which land could be acquired by means of the liberal federal homestead laws; the influx of the land-hungry immigrants from the overpopulated European countries together with the amazingly high rates of increase of the foreign-born and native stocks; the simplicity of life in the new country; and the placement of men following release from military duties after the close of the Civil War — were potent factors in the settlement of the West. Improvements in transportation greatly facilitated settlement and the development of the great resources of the newly opened areas. However, the rapid development of the agricultural potentialities of the West did not have an entirely favorable effect on the older agricultural regions of the eastern states. In many of these areas the competition from the newer, more favored sections soon was keenly felt and necessitated adjustments in eastern production enterprises.

Economic conditions, both as such and as they influence social conditions and the purchasing powers of a people, have an important bearing on crop distribution and the methods of handling crops. These factors determine in the main the standards of living found. In some instances, as with rice production in parts of the Orient and the potato crop in parts of northwestern Europe, a crop is produced and assumes a place of primary importance largely because it yields a greater amount of total food material per unit of area than can be produced by any other crop in that region.

The relation of historical and political influences to present world distribution of crops opens an unlimited field, and a field of study almost untouched by either historians or agriculturists.

Bensin (3) proposes the term "agroecology" to apply to detailed studies of commercially important crop plants by the use of ecological methods. He proposes a systematic collection of data so that the main agricultural regions (agrochoras) of the world and the characteristics of local cultivated varieties of important crops (chorotypes) may be described and recorded by the employment of standardized methods and by a prescribed and uniform terminology. It will be observed that Bensin deals only with the physiological environment of crop plants to the entire exclusion of the social environment.

The excellent works of Finch and Baker (7) on *Geography of the World's Agriculture* and more recent publications, by Buechel (4) on *Commerce of Agriculture*, by Zimmermann (18) on *World Resources and Industries*, and by Jasny (10) on *Competition among Grains*, as well as publications on economic and social geography, will be of great help to the student of ecological crop geography.

Ecological Plant Geography and Ecological Crop Geography. The earlier floristic plant geography gave way with the development and the application of the experimental method to ecological plant geography. Ecological plant geography, put on a firm basis by the works of such men as von Humboldt, Schouw, Meyen, Griesebach, Schimper, and Warming, has a very direct bearing on the subject of ecological crop geography. Distribution and growth characteristics of native plants together with evident soil characteristics offer the most reliable index to the cropping possibilities of a region. As stated by Weaver and Clements (17), "every plant is a product of the conditions under which it grows. It indi-

cates in general and often in a specific manner what other species would do if grown in the same place."

Alexander von Humboldt may, with right, be called the father of plant geography. He gave a preliminary outline of the problems involved in his book *Ideen zu einer Physiognomik der Gewächse* in 1806. His work was followed by Schouw's *Grundzüge einer allgemeinen Pflanzengeographie* in 1836. These were followed by the well-known works: De Candolle's *Geographie botanique raisonée* in 1856; Griesebach's *Die Vegetation der Erde* in 1872; and by the better known and more recent publications of Drude (6), Schimper (13), Warming (16), Clements (5), and Livingston and Shreve (12).

The ecological plant geographer considers only the physiological factors of the environment; since he is dealing with native and primary vegetations he need not take into consideration the effects of the social environment so important to the student of ecological crop geography.

Floristic and Ecological Plant Geography. Floristic plant geography treats the compilation of "floras" and the division of areas into natural "floristic" tracts, together with a discussion of the limits of the species, genera, and families encountered. Ecological plant geography, on the other hand, deals with the underlying causes of the adjustments made by plant communities in their forms and modes of behavior to the ecological factors of their environment. The physiognomy of a vegetation, that is, its general appearance or aspect, is determined not only by the mode of reaction of individual species to environmental factors, but also to a greater extent by the joint response of all species found in a habitat and the consequent grouping and existence or competition, as the case may be, of various species in communities, associations, or formations.

Ecological Crop Geography and Crop Statistics. Ecological crop geography differs from the study of crop statistics as ecological plant geography differs from floristic plant geography. Crop statistics are indeed valuable and essential to the ecological crop geographer as are flora to the botanist or plant ecologist. His task, however, involves more than compilation of figures showing distribution. The ecological crop geographer is concerned especially with the underlying reasons for such distributions, with the grouping of separate crops and the resulting systems of cropping prac-

ticed, as well as the competition found to exist between crops. Above all, crop ecology is concerned with the study of adaptation, or, as Warming speaks of it, the "epharmony" of crop plants. Only through comprehensive investigations of the requirements exacted by various crop plants of their environment can progress in the improvement of these crops be made with the minimum of effort and expense.

Ecological Basis for Agricultural Policies. Under unrestricted conditions centers of crop production tend to develop in those areas to which a specific crop is best adapted. Various national or international circumstances, regulations, and interventions, however brought about, can and have greatly altered the normal or the to-be-expected development of such centers. Production can and has frequently been set up on an artificial basis. The extent to which international trade, including that in agricultural products, is under the influence of widespread governmental intervention is well brought out by a recent study of world trade barriers in relation to American agriculture (1).

Any permanent policy for adjusting production to meet demands brought about largely by curtailment of foreign demand and interference with the movement of agricultural commodities should, to have maximum beneficial effects, be based on ecological relationships. It is necessary to differentiate between emergency and permanent programs. A policy of land utilization, in which ecological and economic relationships would play a prominent part, may well be taken as a basis for the ultimate solution of this perplexing problem. Stewart (14) has outlined such a policy for the public domain with special reference to the management of the grazing lands of the West. A minimum of interference with production in those sections recognized to be adapted to the growing of a certain crop seems logical. If and when curtailment of production is deemed necessary, it is from an ecological standpoint best accomplished by reduction of acreages, or perhaps total elimination, of the crop in those sections where production records have shown that the crop in question is least adapted, or where production is most hazardous, or where the crop has been grown in an artificial environment.

The vital importance of proper land utilization is well recognized by such recently organized agencies as the Soil Conservation Serv-

ice, the Agricultural Adjustment Administration, and the Farm Security Administration. The efforts of these agencies have resulted in marked shifts in agricultural production and in the conservation of both human and agricultural resources. In addition they have decided educational values, stimulate cooperation among producers, and are instrumental in calling national attention to the urgency of the agricultural problem.

REFERENCES

1. "World trade barriers in relation to American agriculture," *Senate Document No.* 70, 1933.
2. Ball, C. R., "Why agronomy needs research in plant physiology," *Jour. Amer. Soc. Agron.*, 17:661–675 (1925).
3. Bensin, B. M., "Possibilities for international cooperation in agroecological investigations," *Internatl. Rev. Agr. Mo. Bull. Agr. Sci. and Pract.* (Rome), 21:277–284 (1930).
4. Buechel, F. A., *The Commerce of Agriculture.* Wiley, New York, 1926.
5. Clements, F. E., *Plant Physiology and Ecology.* Holt, New York, 1907.
6. Drude, O., *Oecologie der Pflanzen.* F. Vieweg & Sohn, Braunschweig, 1913.
7. Finch, V. C., and O. E. Baker, *Geography of the World's Agriculture.* Govt. Printing Press, Washington, 1917.
8. Hansen, A., *Die Pflanzendecke der Erde.* Bibliographisches Inst., Leipsic, 1920.
9. Hesse, R., *Tiergeographie auf Ökologischer Grundlage.* Gustav Fischer, Jena, 1924.
10. Jasny, N., *Competition among Grains.* Food Research Institute, Stanford University, California, 1940.
11. Klages, K. H. W., "Crop ecology and ecological crop geography in the agronomic curriculum," *Jour. Amer. Soc. Agron.*, 20:336–353 (1928).
12. Livingston, B. E., and F. Shreve, *The Distribution of Vegetation in the United States as Related to Climatic Conditions.* Carnegie Inst. Publ. No. 284, Washington, 1921.
13. Schimper, A. F. W., *Plant Geography upon a Physiological Basis*, trans. German by W. R. Fisher. Clarendon Press, Oxford, 1903.
14. Stewart, Geo. R., "A land policy for the public domain," *Econ. Geog.*, 1:89–106 (1925).
15. Tansley, A. G., *Practical Plant Ecology.* Allen & Unwin, London, 1926.

16. Warming, E., *Oecological Plant Geography,* trans. German by Percy Groom and I. B. Balfour. Clarendon Press, Oxford, 1909.
17. Weaver, J. E., and F. E. Clements, *Plant Ecology.* McGraw-Hill, New York, 1929.
18. Zimmermann, E. W., *World Resources and Industries.* Harper, New York, 1933.

Chapter II

THE HISTORICAL BACKGROUND OF AGRICULTURAL PRODUCTION

Primitive Society. Agricultural pursuits antedate recorded history. The earliest means employed by man to obtain a livelihood cannot be designated as agriculture; rather, life was sustained by those gifts that nature had to offer. Yet the problem of securing food and shelter always has been and always will be of greatest concern to man. Social development had no doubt progressed considerably before endeavors to obtain food could be graced with the term "agriculture" or "agricultural practice."

A knowledge of the functions of seeds was of primary importance to agricultural development. The growing of food plants developed to a rather high degree in some areas, notably in portions of both North and South America, without the aid of domesticated animals. The Indian had no beast of burden, unless it was his squaw, of whom Champlain said, "woman is the Indian's mule." Forms of hoe-culture still persist in certain areas, especially in the Orient. Carrier (3) gives a brief summary of speculations relative to primitive agriculture and at the same time points out perhaps the main motivating force for progress.

> "Agricultural pursuits antedate by thousands of years recorded history. Many writers have speculated on the origin of agricultural practices. Some have held that primitive man was first of all a hunter of wild game. Others with perhaps more reasons to justify their conclusions argue that the first human beings on the earth were vegetarians, that they collected plants and seeds for food before they became acquainted with the taste of flesh in their diet. Necessity for sustenance has been the primary force in agricultural progress. The greater the need the greater and more rapid has been the advancement, provided means were available for satisfying that need. Primitive people with a scanty food supply take up new productions with less conservatism than do well-established races with adequate rations."

The Indians of the Great Plains area, having an abundance of food from the hunting of the bison and other animals, were slow to take up plant culture.

The energies of primitive people are directed primarily toward satisfying their few immediate wants, not infrequently with a total disregard of their future existence or well-being. In some instances, as in portions of the tropics, nature may be so abundant with her gifts as not to offer incentives for development or progress. The statement is frequently made that primitive man is completely a creature of his environment, whereas civilized man transforms his environment to suit his needs; yet primitive modes of living and means of sustaining life embody some remarkable adjustments. Thus Tozzer (18) brings out that among the Eskimos the relation of population to land, clothing, food, shelter, tools, and weapons all combine to make life possible in an Arctic environment. Stefansson has shown that the native methods of living are more suitable in every way to the prevailing climatic conditions than anything that the white man can devise. "Man is a most versatile animal when it comes to an adjustment to his geographical environment."

Probable Stages in Early Agricultural Development. Man's methods of securing food for himself and others passed, from all indications, through a series of evolutionary stages. Three more or less well-defined stages in the development of early means of obtaining food and shelter are generally recognized: (1) the hunting and fishing stage, (2) the pastoral stage, and (3) the plant culture stage.

These three generally recognized stages were not identical in all regions; local conditions greatly modified developmental trends, even to the extent of total elimination of one stage, as the pastoral stage in the case of the American Indian. Likewise, it is not always possible to draw clear distinctions between these stages. Neither does the stage in which a particular tribe or group is found always denote the plane of civilization. It is entirely possible that some hunting and fishing people had developed a higher scale of culture than their agricultural neighbors, although that was generally not the case.

The hunting and fishing stage. The hunting and fishing stage has often been glorified by poetic sentiments. Passarge (15) deals at length with the personal and racial attributes that allow only the strongest to survive among tribes gaining their livelihood by the

spoils of the chase. At the same time he points out that an exclusive or nearly exclusive meat diet predisposes these people to various nervous disorders. Some recent investigations by Hahn (9) seem to show that this stage was very indefinite. It is considered doubtful if there ever was a time when man subsisted entirely on the flesh of animals slain in the chase. It is highly probable that early man was on the search for both the animal and plant food products that his environment had to offer.

It can be assumed that primitive man early recognized the importance of obtaining and utilizing a variety of food products for his well-being. Utilizing vegetable foods and realizing their values, man soon observed how his prized plants were propagated. The knowledge of plant reproduction gave rise to plant cultivation.

The pastoral stage. In most cases the second advance was brought about through the domestication of animals. Extensive agricultural development demands the possession of an efficient beast of burden. The transition from hoe- to plow-culture necessitated the presence and use of such animals. The pastoral stage was found especially in the grass regions of Europe and Asia. Certain tribes, such as the Khirghiz of Central Asia, still live the nomadic life of herdsmen. Man now, instead of gorging himself in times of plenty and starving in times of want, had means by which he could tide himself over those periods when natural food supplies were low. The concept of capital was born at this time; wealth was estimated by the ownership of cattle and sheep. Likewise, ownership of land made its first appearance; certain families felt entitled to the utilization of certain areas to the exclusion of others. The system gave rise to the patriarchal family. Land was held not as private but as tribal property. All members of a tribe claimed descent from a common male ancestor. With the increase in the number of tribes and the consequent restriction in the area allotted to each, it became necessary to resort to the production of crops. This led to a more settled population and eventually to the building of villages.

The plant culture stage. The origin of plant culture has already been alluded to. Various planes of plant culture such as hoe- and plow-culture can be pointed out. It is quite remarkable that many of our present crop plants were improved and grown by primitive people. Thus, according to Braungart cited by Dettweiler (4), the Lake-Dwellers of Switzerland living in the Neolithic or late Stone

Age, extending perhaps up into the Bronze Age, that is from about 4000 to 2000 B.C., produced a great variety of crops such as: (1) the dense-cored, six-rowed barley, *Hordeum hexastichon, var. densum;* (2) the short-eared, six-rowed barley, *H. sanctum* of the ancients; (3) two-rowed barley, *H. distichon;* (4) small lake-dwelling wheat, *Triticum vulgare antiquorum;* (5) the so-called Binkel or club wheat, *T. vulgare compactum;* (6) Egyptian or English wheat, *T. turgidum;* (7) a dense-eared awnless emmer, *T. dicoccum;* (8) Einkorn, *T. monococcum;* (9) two kinds of millets designated as *Panicum miliaceum,* and *P. italicum;* and (10) a type of wild flax still growing wild in Greece, *Linum angustifolium.* Munro (14) also lists these same plants as having been grown by the Lake-Dwellers.

The people around the Mediterranean had long grown the cereals and were acquainted with numerous leguminous plants. Oats and dwarf field beans were introduced into northern Europe during the Bronze Age. Millet and oats were the most important crops grown by the Nordic races of Europe.

Carrier gives a detailed description of the crop plants grown by the Indians of North America. The far-reaching effect of Indian contributions to American agriculture is shown in that our agriculture is at least one-third "native American." From the Indian we have such important crop plants as maize, potatoes (both sweet and white), tobacco, peanuts, some varieties of cotton, all the edible beans except horsebeans and soybeans, all varieties of squashes, field pumpkins, sunflowers, Jerusalem artichokes, tomatoes, garden peppers, pineapples, and watermelons. Hedrick (11) gives a long list of plants used by the Indians for food, medicinal, and industrial purposes.

Hoe-Culture and Plow-Culture. Notable civilizations of antiquity, such as those of Egypt and Babylon and, in America, those of the Incas of Peru and of the Aztecs of Mexico, were built on a system of hoe-culture. In the fertile valleys of the Nile and the Tigris and Euphrates, hoe-culture soon gave way to a system of plow-culture. At the time of the Spanish conquest of Peru hoe-culture was still the prevailing system among the Incas; no beast of burden had been domesticated. It is remarkable that these early civilizations — as also the civilizations of Syria and those of the most highly developed tribes of the North American Indians, the Aztecs and Montezumas — developed in arid and semiarid

regions. The practice of irrigation among the peoples of these sections merits attention. The conditions under which crops were grown were worthy of the admiration of the present-day investigator. The methods employed for bringing water from streams or from the mountains to the thirsty fields have astounded even modern engineers.

A number of explanations have been advanced in an endeavor to account for the development of civilizations of antiquity in semiarid regions where irrigation was necessary for crop production. The native vegetation in arid sections can be more readily subdued by human efforts than the heavy forest type of vegetations found in humid areas. Land grown up to trees and even to heavy sods was difficult to clear, especially with the crude tools at the disposal of early civilizations. The open formations common to the semiarid regions were easily cleared and could be made to produce abundant crops with the aid of water. Huntington and Cushing (12) bring out the fact that the development of irrigation farming not only demanded a settled population but also instilled into that population the desire to improve on their physical and social environments. Such improvements could be accomplished only by forethought, industry, peace, and close cooperation of all the people of a given area. Such conditions were conducive to the formation of systems of government, to the development of relatively dense populations, and to the advancement of civilization in general.

The agricultural development of China and India can be traced back beyond the Christian era. In many sections of these countries the agriculture even of today may be classed as a form of hoe-culture. Since the English occupation of India, the agricultural system in some sections of that country has been modified along European lines. In the extremely densely populated sections of southern China and throughout most of Japan the ox (the water buffalo) cannot compete against the cheap human labor.

In the northern European region hoe-culture persisted much longer than farther south, as in the Mediterranean region. It was the system in use by the Germanic tribes at the time of the Roman invasion. After that it soon gave way to a system of plow-culture.

Various forms of hoe-culture can be pointed out. The system followed was dependent mainly on the food requirements of the tribes concerned. In its lowest form seeds were merely put into the

soil and whatever crop resulted was harvested. In more advanced stages certain definite cultural methods were followed. The Indians of North America had prescribed methods of cultivating corn, tobacco, and other crops. It was not long before man observed that certain materials added to the soil tended to increase production. First among such materials were the ashes resulting from the burning of the native vegetations in the process of clearing the land. Numerous references can be found to the early application of marl in European countries. The Indians of Massachusetts adopted the practice of fertilizing their fields with fish. The ancient Peruvians early discovered the value of guano when applied to their fields. The crude beginnings of crop rotation can also be traced back to this early period. Worn-out fields were left fallow, and the grasses and shrubs that were allowed to grow up were burned before the field was again utilized. This system was followed even in early American agriculture. Since land was abundant, little attention was paid to enriching it. Thomas Jefferson said, "We can buy an acre of new land cheaper than we can manure an old one." This is the condition commonly encountered in new agricultural regions. In older civilizations lacking suitable land the question of soil fertility came more and more to the front. It is reported by Middlendorf (13) that the Incas of Peru laboriously removed the surface soils of some of their fields upon exhaustion in order to provide fresh soils for the plants, a practice hardly applicable to humid sections.

Communal Farming. Space does not permit the historical treatment of ownership of land. Early agricultural pursuits may be classified under the heading of communal farming. The total area of crop land surrounding a village was held in common by the inhabitants. Every child in the village became a joint owner of the land. Later the available land for cropping was allotted to the different families. To ensure justice in dividing lands of varying grades of fertility the land allotted to each family was broken up into numerous small strips, scattered over the open fields. Meadow, pasture, and waste lands were held in common for a longer period than the arable lands. After this method of allotting land to families was instituted, private ownership in land began to be recognized. With it came the stratification of society. Various changes took place in land tenure; however, the actual field operations remained

unchanged for many centuries. Venn (19), speaking of conditions existing in England, states, "it is scarcely an exaggeration to say that until the tardy introduction of root-crops, followed by the enclosures of the eighteenth century, the methods of arable farmers had remained substantially unchanged from Anglo-Saxon times." Changes in economic conditions had a greater effect on contraction or expansion of lands under plow than on the methods used in crop production. Yields during medieval times were extremely low; wheat yielded six to eight and barley around ten bushels per acre.

Various forms of land tenure existed in early times. Gras (7), for instance, discusses the small hereditary estates, the slave estates, estates with free tenants, and estates with servile tenants in early Roman agrarian history in the period from 200 B.C. to about 400 A.D. After that period a form of manorial system, later common to central Europe and England, was developed in the Roman Empire.

The Manorial System. A survey of the historical background to agricultural production would not be complete without a brief account of the medieval manor. The manorial system sprang up in all the European countries; its influences are still apparent in the agricultures of these countries. The chief cause for the development of this system, which greatly infringed on the personal liberties of the mass of the population, can be found in the general trend of thought prevailing during medieval times. Eucken (5) states that "authority" more than any other word characterized the spirit of submission fostered by the church and its allied agencies during the Middle Ages. This spirit more than any other factor provided a fertile soil for the development of the manorial system and the general mental stagnation of the masses.

The transformation from the village community to the manor was complex. In England, according to Fordham (6), it was brought about by three major causes: (1) the distribution of the ruler's rights to some favorite; (2) the growth of the military class; and (3) the increase of the burden of taxation on the peasant class. The movement toward the manorial system in England started some time before the Norman Conquest. The Normans found the manor well suited to their needs and did much to strengthen the system. In Germany the manorial system was well established by

the eleventh century. It is held by some investigators that the development of a more extensive system of agriculture through the introduction of the plow was a contributing factor to the establishment of the manorial system. "Whithersoever this implement [the plow] hath gone, bondage and shame have followed in its wake." The rise of the manorial system can also be explained, probably with more weight than should be attributed to some of the other reasons advanced, by the need for security and protection from foes at home and from abroad.

The manor was a complex institution; it was self-sufficient, as was all early and medieval agriculture, except for the necessity of purchasing a limited number of manufactured articles. Along with the system came great specialization of labor; all trades and duties came to be hereditary. Rigid customs, allowing little play for individual initiative, prevailed. Agricultural production made little progress. The manor was instrumental in perpetuating the open-field system with all its disadvantages.

The manor in England may be said to have had four ages: its growth period extended from 800 to 1200; its height was reached in the thirteenth century; it was on the decline from 1300 to 1500; after 1500 it survived only in nonessentials. The conditions directly leading to the fall of the system in western Europe were (1) the numerous wars; (2) the Black Death; (3) religious and social agitations; and (4) the peasant revolts. The incessant warfare indulged in by the nobility led to heavy taxation, with the peasants carrying the major burden. Of these wars the Hundred Years' War, 1338–1453, between England and France was of greatest consequence. The Black Death, striking England in 1348–1350, after having swept Europe from east to west, cut down on the supply of available labor. It is estimated that one-third of the population of England succumbed to the disease. Religious and social agitations, often lacking in leadership and close cooperation, kept the masses stirred up and clamoring for reform.

The manorial system survived longer in central and eastern Europe than in the west. In Prussia and Austria the system survived more or less unaltered up to the reigns of Frederick the Great and Maria Theresa. The backwardness of these countries can be attributed in a large degree to the devastating influences of the Thirty Years' War.

The Seven Years' War convinced Frederick the Great that the military value of the peasant classes could be enhanced by some degree of liberation. This, more than any other consideration, caused him to take steps in that direction in the Act of 1749. Yet really effective reforms did not come to Prussia until after the Napoleonic invasion. The disaster of the battle of Jena, 1806, brought out the need of definite reform (Abbott, 1). The revolutionary principles of "liberty, equality, and fraternity" were of tremendous help to Napoleon in his successive victories over Austria and Prussia.

In Russia the manorial system survived even longer. It was shaken somewhat by the after-effects of Russia's defeat in the Crimean War, 1853–1856. The decree of 1861 abolished all legal rights of noblemen over peasants, but even then complete liberation was not accomplished. As stated by Hayes (10), "it has been remarked wisely, though possibly a little strongly, that the decree of Alexander II freed the peasants from the nobles only to make them serfs of the state." The disaster of the Russo-Japanese War of 1904–1905 was followed by agitations and some degree of liberation. The final rupture came in 1917 following the herding of the peasants to slaughter in the first World War.

Transition from the Medieval to the Modern Period. All progress from the Middle Ages to the modern period was intimately associated with the transition in trends of thought from the former to the latter period. This phase of the discussion may well be summarized by the main characteristics of modern philosophy enumerated below.

1. Belief in the possibility of progress. Medieval thought was concerned with maintaining the *status quo*. More thought by far was given to spiritual than to the material existence of man.
2. Discovery of nature as interesting in itself and promising much for improvement when properly understood and controlled. Here is given a place for the development of modern science. Credit belongs primarily to Francis Bacon for investigating and arousing interest in this phase of human speculation after long neglect and periods of inactivity since the days of the active Greek philosophers.
3. The repudiation of tradition.
4. The growing appreciation of the value of human life on its own account.
5. Emphasis on the natural possibilities of man.

6. The development of individualism. The liberation from traditions together with the realization of man's own possibilities resulted in a freedom not before possible and an expression of individual ideas.

7. The attempt to free man from the domain of the supernatural. This effort directed his attentions more to his physical and less to his spiritual existence.

8. Thought tends to be revolutionary in that modern man is not only willing but anxious to put to a test new ideas in the solution of his problems.[1]

Eucken (5) sums up the transitions of thought from the early to the modern period in an admirable manner.

The march of progress in agricultural pursuits as well as in other lines of endeavor was markedly influenced by this change in philosophy. The further progress of agriculture was also closely associated with progress in the sciences and in experimental research.

The Mercantile System. Mercantilism, according to Spann (17), may be termed a new kind of economic practice involving a number of novel and interdependent theories making their appearance at the opening of the modern era. The advocates of the system were concerned with the exchange of merchandise and the promotion of industrial development. The dominating feature of these series of economic policies was a great esteem for money and for foreign trade. Industry was looked upon as the precursor of commerce. The primary object of the mercantilists was to achieve for their respective countries a favorable "balance of trade" with the objective of increasing the amount of money in the country. To do this it was necessary to stimulate export trade of manufactured articles and to reduce to a minimum the purchase of such goods. While such a system led to a certain amount of freedom of trade and laid the foundations of our present industrial state, it was not always favorable to agricultural development. In the effort to gain the object considered of prime importance to the advocates of the system the export of raw materials was prohibited in many countries. France prohibited the export of grain; Frederick the Great, of Prussia, decreed corporal punishment to any one who should export wool. This was a decided disadvantage to agriculture. It impoverished the agricultural classes and prevented the

[1] These points are taken from a series of lectures on the "History of Philosophy" given by Dr. M. T. McClure at the University of Illinois in 1925.

formation of centers of production of commodities to which certain countries were best adapted. It tended to preserve self-sufficient types of agriculture since it hindered application of the theory of comparative advantage. In passing it should be mentioned that the mercantile system provided fertile groundwork for the development of intense nationalism with its drastic effects on the world distribution of crop plants.

The Physiocratic System. The mercantilists' confusion of economic wealth with the possession of precious metal led eventually to the belief that the system was responsible for certain fiscal difficulties. This together with the restrictions against the export of grain and the consequent low prices for that commodity resulted in the swing of the pendulum to the opposite extreme. The physiocrats under the leadership of Quesnay enthroned agriculture as the only creative occupation; other workers, he held, performed only a work of addition, of transformation, or of transport. "L'agriculture est la source de toutes les richesses de l'état." To the physiocrat the essentials of an equitable economic system should guarantee to the individual personal liberty, the free choice of occupation, freedom of industry and consumption, freedom of movement from place to place, and freedom of private property. These essentials are summarized in the famous motto "Laissez faire et laissez passer, le monde va de lui-même" (Let do and let be, the world goes of itself).

The physiocrats expounded their theories in France; the poor state of agriculture during the eighteenth century had, no doubt, much to do with the formation of their ideas. That the tiller of the soil be considered as the only creative worker is, of course, a gross overstatement. True, the agriculturist produces food products and feeds other toilers of industry, commerce, and the professions. Yet, from the standpoint of utility, the services rendered by these latter classes are by no means sterile.

Even though the main theories promulgated by the physiocrats rested on an infirm foundation, they had a very decided effect on agricultural production. They promoted a degree of individualism without which commercial agriculture could not have developed. Their influence was great, especially in the new agricultural regions of the world opened up for settlement during the course of the nineteenth century.

Recent Stages in Agricultural Production. The main changes in philosophy from the medieval to the modern period have been discussed. These decided changes in trends of thought had a profound effect on agricultural development. Four more or less well-defined stages in the development of agriculture during the modern period may be pointed out: (1) the development of scientific agriculture; (2) the development of commercial agriculture; (3) the development of mechanized and highly specialized agriculture; and (4) the very recent period of intense national feeling and attempts to achieve national self-sufficiency in agricultural production.

Scientific agriculture. The development of scientific agriculture is intimately associated with discoveries in science and with the applications of these findings to agricultural problems. Scientific rotation of crops with the view of establishing a permanent system of agriculture became established with the greater and more extensive use of legumes. As a result crop yields were increased and periods of scarcity and actual famine became less frequent. Specialization in production, the growing of crops in sections especially adapted to their production, had its beginnings during this period. This was decidedly at variance with the old medieval self-sufficient type of agriculture. The marked improvements in methods of transportation during the seventeenth century and the transition from village to town economy greatly furthered specialization in production.

Russell (16) outlines three periods in the historical development of conceptions of the requirements of plant growth: (1) the search for the "principle" of vegetation, 1630–1750; (2) the search for plant nutrients, 1750–1800; and (3) the modern period.

During the early period investigators were imbued with the idea of discovering some one "principle" to account for the phenomenon of soil fertility and plant growth. Space does not permit the enumeration of the accomplishments of the modern period. There were the great accomplishments of Boussingault, who laid out a series of field plot experiments on his farm at Bechelbronn in Alsace in 1834; Sprengel's work on the ash constituents of plants; Schübler's investigations in soil physics; the great works of Liebig in Germany and of Lawes and Gilbert in England. It remained the task of Hellriegel and Wilfarth to demonstrate that the fixation of

nitrogen by legumes was a biological process. This was accomplished in 1886; two years later the organism concerned was isolated by Beijerinck. During this period very marked improvements were made in all crops and animals as also in general agricultural practices.

Commercial agriculture. Agriculture was greatly influenced by the establishment of metropolitan economy during the last century. Vast new regions in North and South America, Africa, and Australia were thrown open to agricultural production, and agriculture in the older sections greatly improved. The tremendous increase in world population and the impetus given by the industrial revolution were influential in the ever-greater specialization in the production of agricultural commodities. The self-sufficient agriculture of older regions gave way to specialization; production here was modified through the availability of cheap products from the newly exploited areas. Food and other commodities became more abundant than in any previous period of history. The warning of the possible dangers in increasing populations sounded by Malthus at the end of the eighteenth century was not considered serious in the face of the new abundance. Scientific discoveries were effectively applied to agricultural production, industry, and transportation. The "tempo" of exploitation, as it is called by Zimmermann (22), was speeded up to tremendous rates. A spirit of optimism promising an entirely new basis of civilization was engendered by the new tools put at the disposal of mankind. Wright (21) presents a vivid picture of the new age with special reference to the population problem.

> "The progress of civilization has enabled man to exercise a constantly increasing control over nature and to wring a larger and larger supply of food from the earth, but never, probably, until the middle of the nineteenth century has human subsistence been brought within measurable distance of the reproductive power of the race. At that period, the rapid development of natural resources in North America, rendered possible by the no-less-rapid development in Europe, especially in Great Britain, of coal and iron and the manufactures depending upon them, gave to the white races of Western Europe the extraordinary experience of a supply of things for human consumption increasing even more rapidly than the population could do with an almost unrestricted birth-rate. Increasing returns to every dose of capital and labor applied either to agriculture in the New World or to manufacturing in

the Old were obtained for a time. The standard of living rose, the cost of living continued to fall, and man's conquest over nature seemed well-nigh complete. Then it was that in spite of the warning voices of Mill and Jevons the progress of the human race towards material and spiritual perfection was generally in Western Europe believed to be continuous and inevitable. Malthus with his Principle of Population and Ricardo with his Law of Diminishing Returns were discredited."

Mechanized and highly-specialized agriculture. Call (2) in speaking of the efficiency of American agriculture calls attention to four factors: (1) the discovery and introduction of new crop plants, especially of such plants as early varieties of spring wheat, hardy varieties of winter wheat, the sorghums, and legumes such as alfalfa and sweet clover, all of which were effective in advancing the agricultural frontier into the drier areas of the west and the shorter season areas of the north; (2) the use of mechanical inventions and power which shifted the burden of production from human to horse- and motor-driven equipment, making the tasks of the producer less arduous and greatly increasing his efficiency; (3) the application of science to production, improvement, and protection of plants and animals; and (4) the education of the American farmer and his family.

The application of power equipment opened vast areas to production. To what an extent harvesting operations alone have been simplified and brought to a high state of efficiency since the days of the invention of the reaper by McCormick in 1831 is shown by a citation from Walker (20).

"A century ago an able-bodied man could cradle two acres of wheat in a day, and it took two other men to bind and shock what he had cut. Or in other words it required three men to cut, bind and shock two acres of wheat in a day. With the present day harvesting machines, such as a 20-foot combine pulled by a modern tractor and with a farm motor truck for hauling grain, an equal number of men in a western Kansas wheat field can cut, thresh and deliver to market a distance of two miles forty-five acres of wheat in a day. This is fifteen times the acreage cut, bound and shocked by the three men of a century ago. Moreover, the work of the present-day harvest hand is less arduous and much more interesting."

The application of motive power increased agricultural production in two ways: (1) by causing new lands not previously used for the production of crops to be brought into production; and (2) by

releasing large acreages of crop and pasture land formerly required to feed work animals replaced by tractors and trucks for the direct production of cash crops. According to Gray and Baker (8), around 20 to 25 million acres of crop land were released for other uses as a result of the rapid adoption of tractors, trucks, and automobiles in the United States from 1918 to 1929, truly a substitution of inanimate for animate sources of energy. Stored-up solar radiation is used as a source of energy.

It has been stated that a greater expansion in agricultural production resulted from the above factors than subsequent world economic conditions at the time demanded. For the time being a halt has been called. Retrenchment of production appears imminent. It should be carried out along lines of logical land utilization. Production should recede on an ecological basis.

Intense nationalism. The first World War and the world depression ushered in a period of intense striving toward a national agricultural self-sufficiency. This caused developments running counter to the trends toward specialization in the world production of agricultural commodities and called for decided changes in agricultural policies in the import and adjustments in the export countries.

REFERENCES

1. Abbott, J. S. C., *The Life of Napoleon Bonaparte*, Vol. 1. Harper, New York, 1854.
2. Call, L. E., "The increased efficiency of American agriculture," *Science*, N. S. 69:54–60 (1929).
3. Carrier, L., *The Beginnings of Agriculture in America.* McGraw-Hill, New York, 1923.
4. Dettweiler, "Aryan agriculture," *Jour. Heredity*, 5:473–481 (1914).
5. Eucken, R., *The Problem of Human Life*, trans. German by Williston S. Hough. Scribner, New York, 1910.
6. Fordham, M. A., *Short History of English Rural Life.* G. Allen & Unwin, Ltd., London, 1911.
7. Gras, N. S. B., *A History of Agriculture in Europe and America.* Croft, New York, 1925.
8. Gray, L. C., and O. E. Baker, "Land utilization and the farm problem," *U. S. Dept. Agr. Misc. Pub.* 97, 1930.
9. Hahn, E., *Das Alter der Wirtschaftlichen Kultur.* Heidelberg, 1905.
10. Hayes, C. J. H., *Political and Cultural History of Modern Europe.* Macmillan, New York, 1932.

11. Hedrick, U. P., *A History of Agriculture in the State of New York.* New York, Agr. Exp. Sta., Geneva, 1933.
12. Huntington, E., and S. W. Cushing, *Principles of Human Geography.* Wiley, New York, 1924.
13. Middlendorf, *Peru.* Berlin, 1894.
14. Munro, R., *The Lake-Dwellers of Europe.* London, 1890.
15. Passarge, S., *Landschaft und Kulturentwicklung in unseren Klimabreiten.* Friederichsen & Co., Hamburg, 1922.
16. Russell, E. J., *Soil Conditions and Plant Growth.* Longmans, London, 1927.
17. Spann, O., *The History of Economics*, trans. German (19th ed.) by Eden and Cedar Paul. Norton, New York, 1930.
18. Tozzer, A. M., *Social Origins and Social Constituents.* Macmillan, New York, 1925.
19. Venn, J. A., *Foundations of Agricultural Economics.* University Press, Cambridge, England, 1923.
20. Walker, H. B., "The combine, a factor in wheat production," *Report* of Kansas State Board of Agriculture of the quarter ending March, 1927.
21. Wright, H., *Population.* Harcourt, Brace, New York, 1923.
22. Zimmermann, E. W., *World Resources and Industries.* Harper, New York, 1933.

Chapter III

POPULATION IN RELATION TO AGRICULTURAL DEVELOPMENT

Population and Agriculture. "Hunger and new ideas are two advocates of change which plead best in each other's company; hunger makes men willing to act, and new ideas give them matter for enactment." These words of Bonar (1) may well be applied to the problem created by increasing population and less rapidly increasing supplies of available food. Population growth and food supplies are closely related. Yet, because of the complexity of the problem, a great variety of factors must be considered in the relation of agricultural development to increases, and rates of increases, in the numbers of the human species. While the pressure for the means of subsistence often may have stirred man to activity, it was by no means the only factor making for advance. As a matter of fact, the time and energy of a people may be drawn upon to the extent of greatly interfering with advance and the furthering of culture traits. Again, nature may be so abundant with her gifts as to offer no incentive for exertion and progress. If under such conditions population increases beyond the means of subsistence, drastic means may be resorted to in order to keep the numbers of a tribe within certain limits. Not infrequently, however, necessity becomes the mother of invention. An increasing population and the subsequent pressure for food have in times past and will, no doubt, in the future lead to more and more intensive studies of problems involved in the production and the distribution of food and other agricultural products. A brief consideration of the growth and demands of population merits the attention of the agricultural scientist.

The Population Problem. No attempt will be made here to summarize the voluminous literature on population and population growth. Exhaustive studies of the problem may be found in the published works of Bowen (2), Carr-Saunders (3), East (4), Pearl

(10), Thompson (16), Reuter (12), Wright (20), and other investigators.

The population problem divides itself into two phases, (*a*) the quantitative and (*b*) the qualitative features. Obviously both are of great importance. The qualitative aspects of the problem fall mainly in the fields of eugenics and genetics. The quantitative feature, dealing more directly with the numbers of a population rather than with its composition, has a more direct bearing upon the questions under discussion here.

The main features of the population problem, some of them quite evident, having a direct bearing on agricultural production may be briefly stated in the following twelve points. These twelve points by no means circumscribe the entire problem; there are many social and economic aspects.

1. Man in order to survive must have food, clothing, and shelter.
2. It is the task of agriculture to provide the major portion of the means by which life can be sustained.
3. There is a definite man-land ratio which cannot be greatly altered without effecting modifications in the arts, the standard of living, or the cultural development of a people. Changing conditions demand adjustments either on the man side or on the land side of the ratio.
4. Agricultural production can be increased greatly, through development and application of the arts, beyond its present limits should the demand arise and society feel inclined to pay for such expansion.
5. The law of diminishing returns applies to agricultural production; it cannot be set aside. Beyond a certain limit an increasing number of either hands or heads cannot produce a corresponding increase in food supplies.
6. Economy in production and the judicial use of land demands recognition of the population problem. Agricultural production until recently was geared to rapidly increasing populations. The recent slowing down of such rates of increase calls for adjustments in the tempo of agricultural production and exploitation.
7. Man has a great propagating capacity or fecundity.
8. Without the intervention of definite checks, either imposed by nature or self-imposed by man, population would soon increase to a point beyond the most optimistic estimate of the possible means of subsistence.
9. World population has been increasing over a long period of time; it has increased at an especially rapid pace throughout the last century and during the beginning of the present century and is still

10. Psycho-economic forces and the spread of knowledge of birth-control methods have been instrumental in lowering birth rates in Western civilizations and may be expected in the future to hold rates of increase down to certain more or less desired limits. In the over-populated sections of the Orient natural forces are most effective in preventing rapid increases in population. The more enlightened nations of the Orient, like Japan, may from all indications soon be expected to apply Western methods to their population problem.

11. While birth rates in countries of Western civilization have decreased markedly, mortality rates have also decreased. The salvage of human life resulting from this may be explained by the great advances made in medical science, in sanitation, in engineering devices affecting water supplies and disposal of sewage, and above all by the greater abundance, quality, and variety of food products available. Improved nutriment is the greatest foe of death and disease.

12. It is exceedingly difficult to make reliable predictions relative to future behavior of populations, rates of increase, or even possible declines. With an increasing desire for a higher standard of living and means at hand to regulate birth rates, intelligent population control may be expected to keep population within the limits of the means of subsistence.

The Growth of Population in Primitive Societies. The rate of increase in population of primitive societies is dependent mainly on their state of culture. Wissler (19) points out that the number of Indians inhabiting the plains of North America was extremely low in relation to the present and the potential population of that region. The culture of the Red Man of necessity had to succumb to that of the advancing white settlers before the region could support a larger population than was possible under the hunting and crude plant culture complex. As stated by Wissler, "one fact stands out in human ecology, viz., that under a given culture the tribal group expands until it reaches the limit of its food supply; then if it does not succumb, or remain static, it evolves a new mechanism for feeding itself, only to repeat the phenomenon over once more." Sumner and Keller (14) make a similar observation.

Aside from the stage of culture, which in itself is determined to a large degree by environmental factors, the population of a primitive tribe is determined mainly by factors leading to a scarcity or abundance of food. The elements of the climate are in this respect of greatest consequence insofar as they determine the availability of food as well as the food requirements of man. Since population tended to increase up to and often beyond the limits of its food

supply, there resulted a constant struggle to provide the means of subsistence. According to Keller (8), savages have no real "population policy" even though such practices as abortion and infanticide are frequently resorted to in order to keep down numbers. Keller terms such practices traditional rather than rational.

Centers of Civilization. Favorable environments favor increase in numbers. Culture traits developed in those areas where environmental conditions were favorable to a relative concentration of members of the human species. The man-land ratio was then influenced by means of improvement in the arts. Using Sumner and Keller's terminology, "it is the arts that must carry any increasing burden of numbers." Areas favorable to the necessary initial concentration of population and the beginning and development of the arts of cultivation were found in the river bottoms of the warmer temperate regions of the Old World — in China, Northern India, Assyria, and Egypt. Here were found, according to Gregory *et al.* (7), the first foci of civilization. Attention is called to the fact that these early centers of civilization developed in relatively dry regions where irrigation became necessary to ensure stable crop production. The early centers of civilization in America, those of the Incas, Aztecs, and Montezumas, also developed in dry areas. The possible influence of irrigation on the promotion of civilization has already been discussed.

Greek and Roman Population Theories. The ancient Greeks approached the population problem from the standpoint of the ideal City State. Both Plato and Aristotle were conscious of the dangers involved in overpopulation. One of Aristotle's criticisms of Plato's *Republic* was that Plato did not sufficiently meet this difficulty.

More drastic means were resorted to in Sparta than in Athens to secure the proper man power for military purposes. Here, greater emphasis was placed on the quality of the population; weak infants were exposed so that they would not fall burden to the state. There seems to have been little fear of overpopulation in Sparta; the number of slaves was kept in check by infanticide, while frequent wars served to keep down the number of freemen. Population policies aimed primarily toward an increase in the numbers of the states' military forces.

In Rome, an increase in population was actively stimulated.

The rearing of legitimate offspring was conceived to be a public duty. Marriage existed for the purpose of rearing citizens for the state and soldiers for the army. Various laws against celibacy and childlessness were passed. As in Sparta, awards were given for large families. Yet the experience was identical with that of nations of modern times who have attempted to increase birth rates; the rates of increase among the upper classes remained low. The numerous military expeditions were a heavy drain on the man power of the empire.

Influences of Christianity. Early Christianity rather discouraged marriage, which was looked upon as an inferior state, to be tolerated but not to be encouraged. This was a decided reaction to trends in Rome. The fathers of the church paid scant attention to political and economic considerations. As stated by Reuter, "in its medieval form the Christian doctrine was not favorable to fecundity."

The Middle Ages finally gave rise to a period of strong national feeling. With this rise of national consciousness came profound changes. The church with its authority no longer discouraged increases in population but, seeing strength in numbers and being closely associated with the military parties, began to foster fruitfulness and proceeded to bestow its blessing upon it. Thus, according to Bowen, "in the Middle Ages a great deal was heard of Christian soldiers and the armies of Christ; the cross and the sword became so mixed up that swords were made in the form of the cross, and the impress of the cross and the blessings of the church were given to all implements of destruction." Attention should be called to the numerous religious wars of medieval Europe, of which the Crusades and the Thirty Years' War stand out as bloody examples.

Even after the Reformation, authorities of the church had little conception of the population problem. Thus, Luther states, "Gott macht Kinder der wird sie auch wohl ernähren." Because of theological bias the problem was seen as a moral one; an implicit faith in nature was cultivated.

Population of Medieval Europe. No accurate figures of the population of medieval Europe are available. Some estimates have been made, however. At the time of Christ, the population of Europe was probably less than 5 million. At the time of the

Norman Conquest, A.D. 1066, it was estimated at around 10 million. Mulhall estimated the population of Europe in the fifteenth century as around 50 million. Willcox (18) approximates that the constituents of the six language groups, English, French, German, Italian, Russian, and Spanish, amounted to probably 50 million in 1492, or about one-ninth of their present number.

From all indications, population increased rather slowly during medieval times. Plagues, epidemics, famines, wars, and other catastrophes were interpreted as the instruments of God, used to chastise and to teach his people, and were, therefore, regarded as natural happenings. It was considered irreligious and a form of heresy to inquire into the causes of these disasters which swept down on unsuspecting humanity from time to time and kept their numbers in check.

Effects of Mercantilism. A definite trend toward denser population became evident around the middle of the sixteenth century. The efforts of the mercantilists to foster foreign trade and industry created a demand for laborers. As a result, all possible agencies were applied to foster increase in population. Improvements in commerce and the means of transportation had much to do with the realization of this desire. An exchange economy took more definite shape than before; agriculture started to drift from the old self-sufficient pattern to one of specialization. Conditions in general favored the growth of population.

Population growth was fostered through economic and militaristic motives. A few quotations from writers and theorists of the time will serve to bring out the emphasis put on the importance of numbers. Thus, Thomas Mun in advocating denser populations wrote: "For when a people are many and the arts are good, there the traffic must be great and the country rich." Thomas Temple wrote: "The true and natural wealth of nations is the number of people in proportion of the compass of the ground they inhabit." Zincke states: "All legitimate means must be used to maintain a constant increase in the population of a country." And the words of Justi read: "A land can never have too many inhabitants." Vauban makes a very typical statement: "By the number of their subjects is measured the grandeur of kings." Even Adam Smith comes out with a statement taken from Bowen very much in line with the philosophy of the mercantilist, the

militarist, and the churchman of the time: "The most decisive mark of the prosperity of any country is the increase in the number of its inhabitants." Later Smith makes a statement with a slightly Malthusian color: "Countries are populous, not in proportion to the number of people whom its produce can clothe and lodge, but in proportion to that of those whom it can feed."

The mercantilists placed emphasis on numbers; they were concerned only slightly with the living conditions of the masses. Scant attention was given to the relationship between increasing populations, possible food supplies, and the comforts of life. It is undeniably true that the most favorably endowed areas of the world are the most populous. However, the reason for the richness of these areas is not to be found in the density of the population; rather, populations are dense because of the favorable environment. The mercantilists had not realized the fact brought out so well by Bowen, who states: "This theory of progress through over-propagation results in two opposed doctrines of population; the political and the economic. The political exhorts man to propagate and prevail; the economic to be cautious and comfortable."

The Industrial Revolution. By the end of the eighteenth century practically all sections of Europe were populated to the greatest possible extent that could be supported under the agricultural, economic, and social regime then prevailing; there was a definite approach to ideas of Malthus. Certain sections had reached the saturation point, and emigration on a large scale had not yet begun. Population had increased rapidly, while the art of food production had made but little progress. Exchange economy was still backward, and while agriculture had made some progress toward specialization, it was still of rather local proportions. World trade in agricultural commodities was only beginning. The masses were destitute. Yet, many political economists still clung to the old idea that national strength was determined by numbers alone. It is no small wonder that many of them were distrustful of the doctrines advanced by Malthus.

Then came a rapid succession of mechanical inventions, and with them was ushered into existence a new industrial system. Home industries gave way to machine and the factory type of industry, accompanied by a wage system. The development of manufacturing was more rapid in England than on the Continent,

which remained largely agricultural, except for small areas, until the latter part of the nineteenth century.

After the initial period of adjustment, the development of manufacturing gave work to the masses. With the increasing development of an exchange economy, the fruits of their labors were used to bring food supplies to the new industrial centers. The new agricultural regions, especially in North America and later in South America, Africa, and Australia, served as ready markets for manufactured articles offered in exchange for the raw products and especially the agricultural products that they produced. With relatively unrestricted, or free, trade relationships, with marked improvements in means of communication and transportation, and with vast natural resources at man's disposal for exploitation, world trade developed at a very rapid rate. Agriculture grew from a task of merely local proportions to a world industry. The industrial revolution resulted in the specialization of labor in the field of industry; in agriculture, it resulted in the specialization of production. Sections with climatic and soil conditions especially adapted to certain crops, such as wheat, rye, or tobacco, specialized in the production of these crops. The advantage of such a system from the standpoint of conserving human energy is quite evident. However, it does call for a complicated system of distribution. As a result, when the established economic systems are thrown out of adjustment for any reason, one may expect, for the time being, a reversal in the process, or a tendency to revert to the older self-sufficient type of production.

Vegetable and Machine Civilizations. All sources of energy in the final analysis may be traced to stellar, chiefly solar, radiation. There are two main sources of energy available to man: (*a*) the current and very recent receipts, and (*b*) the stored-up supplies. The first would be the energy derived either from the direct utilization of plants or plant products or from the utilization of animals or animal products. This energy is directly traceable to recent plant and vegetable growths. The second class of energy is also traceable to plant life, but was fixed at some distant period. Under this class are found the fuels, such as coal, oil, natural gas, and peat, and the various products that can be derived from them. All these forms of energy are fixed by means of the photosynthetic process of plants. The first form of energy supply is called animate,

the second inanimate, energy. Civilizations dependent solely upon muscle power, that is, the energies produced by man and domesticated animals, are designated by Zimmermann (21) as "vegetable civilizations." Civilizations making extensive use of motive power are referred to as "machine civilizations."

One of the greatest handicaps in the vegetable civilization is the lack of mobility. The energy available is not sufficient for the development of rapid and efficient means of communication and transportation. As a result of this deficiency, a closed or locally self-sufficient economy prevails. The development of a machine or technological civilization with its greater employment of inanimate energy in production, communication, and transportation was a vital factor in the establishment of world trade and in the resulting specialization in agricultural production.

World Population Increases from the Beginning of the Nineteenth Century. The nineteenth century witnessed a most remarkable increase in population, not only in Europe but also in all the other continents. This was to be expected in view of the abundance of natural resources to be exploited with the new tools so recently placed at the disposal of humanity. It was decidedly a period of expansion. Another contributing factor is to be found in the fact that birth rates remained at rather high levels throughout the nineteenth century while death rates in all the Western countries were markedly lowered by improved living conditions, improvements in sanitation, and advances made in medical knowledge. The population of Europe increased from 200 million to 456 million, of Asia from 400 to 870 million, of Africa from 100 to 140 million, and of the Americas from 20 to 205 million.

The remarkable increase in the population of both North and South America is readily explained by immigration and the high birth rates of the new settlers. The high birth rates are directly traceable to the abundance of natural resources and the general philosophy of the times favoring large families. These two continents offered room for expansion for the multitudes of overcrowded Europe.

The most amazing fact is the great increase in the population of Asia. The reason for this may best be found by an analysis of population increases in the three great centers of population of that vast continent, namely, China, Japan, and India.

The best estimates available place the population of China at around 400 million. Indications are that it remained practically constant during the nineteenth century. The birth rate is high — according to some authorities, 50 per 1,000 as against 18 per 1,000 in nations of the Western civilizations. But the death rate is also high. Sanitary conditions are poor, and proper food for infants is not available. "China," says Ross (13), "offers a living example of conditions as they existed in Medieval Europe. The lack of sanitation and proper food is counteracted by the great fecundity of man, a wasteful method indeed, but the Chinese survive."

Japan experienced a great increase in population after opening its doors to European and American commerce. Before that time the population of the islands seems to have been practically stationary. The Japanese, unlike the Chinese, sifted from the Euro-American culture those traits that could be of help and use to them and could be readily assimilated. The population of Japan has increased almost threefold during the past century.

India, like Japan, through European intervention, was able to increase its numbers greatly. As stated by Wright: "British rule has done much to improve conditions of life in India but it has also cut away many of the checks to population which formerly prevailed there." In 1851, the population of India was estimated at 178.5 million; in 1930, India had a population of 352.4 million souls. As pointed out by Wattal (17), British intervention not only served to remove in part the existing checks but also provided means for improving and increasing agricultural production. Vast sums have been expended for irrigation developments and on research of pressing agricultural problems.

Population Trends during the Early Part of the Twentieth Century up to the First World War. The industrial or mechanical revolution gave rise to centers of manufacturing and the consequent ability of the masses to purchase food supplies from distant centers of production. Technological advances and advances in medical science ensured better health and greatly lowered the death rate, while birth rates continued at fairly high levels. These were in brief the main factors responsible for the phenomenal increases in world population during the last century. That rates of increase remained high during the very early part of the present century is evident from Table 1, showing the rapidity with which certain

countries were increasing their populations in the period 1905–1911.[1]

TABLE 1. RATE OF POPULATION GROWTH IN CERTAIN COUNTRIES FOR THE PERIOD 1905–1911

Country	*Rate of Increase per 1,000*	*Number of Years Required to Double*
France	1.6	436
Norway	6.6	105
Sweden	8.4	83
Austria-Hungary	8.5	82
Spain	8.7	80
England	10.4	67
Japan	10.8	64
Holland	12.2	57
Germany	13.6	51
Rumania	14.8	47
United States	18.2	38
Australia	20.3	34
Canada	29.3	24

The rate of increase of the white race was especially high. The reasons for this are not far to seek. At the present time the white race has political control of 90 per cent of the habitable areas of the globe. This alone removes the check under which the colored races, especially the yellow, are laboring. There are yet many regions under control of the white race which have reached neither the saturation point for population nor their point of maximum production.

To the white race can be attributed the distinction of having a wider range of climatic adaptation than any other race. This, together with their knowledge and skill in making a region originally unfit for white colonization fit for the white race, has been of great help in gaining the present supremacy in numbers.

Another factor contributing to the supremacy of the white race is brought out in the studies reported by Sweeney (15). The vital index or, as Pearl designates it, the birth-death ratio, computed by the formula $\frac{100 \times \text{births}}{\text{deaths}}$ was used to evaluate the health of different populations. If the ratio for a given population yields values

[1] This table, taken from East, was cited from Knibb's work, *The Shadow of the World's Future.*

of over 100, then it is growing and in a healthy condition. If the ratio is less than 100, the population may be considered biologically unhealthy. It became evident from the studies conducted by Sweeney that the populations of the northern European races, of the Australian races, and of Canada and the United States had higher vital indices and may, therefore, be regarded biologically healthier than other peoples.

The Man-Land Ratio. At the rate of increase prevailing in 1923, the population of the world will reach, according to East, 5,200 million in a little over a century. Since this statement was written there has been a decided decrease in the birth rates in all Western countries, and it may be said that there is no immediate prospect of the rates regaining their former levels. Another factor to be considered is that with declining birth rates the mean and mode of the age classes tend to shift to a higher age level, which will result, unless counteracted by other factors, in a somewhat higher death rate in the future. It is safe to say that the experiments reported by Pearl (10) on the rates of growth of populations of fruit flies (Drosophila) influenced East in arriving at his estimate of future human population. That the rates of increase of man are to a considerable extent determined by his own volition is becoming increasingly evident by the falling birth rates of the countries influenced by machine civilization. Psycho-economic factors have affected rates of increase and no doubt will affect them in the future. The desire for a higher individual standard of living, especially on the part of people who have experienced a fuller life, has a very decided depressing effect on birth rates. Or, as one notably moral reviewer of Senior's Oxford Lectures of 1828 quaintly phrased it: "More persons will rather dine alone on champagne and chicken than share their roast beef and pudding with a wife and family." The "wife and family" add, no doubt, to the joy of life of a great number of people, but the tendency is to keep the family small. To quote Bowen: "Having children for the greater glory of God or Country, which is to say the manufacture of pew renters and cannon fodder, is not the modern mode."

Gray and Baker (5) give graphically the trends of birth rates in five countries of northwestern Europe. All countries show a decided downward trend. According to these authors: "The rate of decrease in birth rates is greater than in death rates. If the trend con-

tinues, stationary population in the highly industrialized countries appears inevitable."

Birth rates are following the same general trend in the United States as in the industrial countries of Europe. The birth rates are higher in the rural states than in the urban states; however, both have been decreasing at about the same rate since 1921. The higher birth rates in the rural states are to be expected in view of the fact that children on the farm are less of a liability and interfere less with the freedom of their parents than under urban conditions. To use the words of Gray and Baker:

> "The birth rate is declining so rapidly that if the rate of decline continues for another seven years the number of births will not be sufficient to maintain the population of the country when the children of today reach maturity. Assuming no important change in the volume of immigration, our population appears to be gradually approaching a stationary stage, which will be attained in from 30 to 40 years, when, it seems probable, the Nation's population will be between 150,000,000 and 170,000,000."

Pearl *et al.* (11) estimate the population of the United States to reach about 175,000,000 in the year 2000. The implications of a possible stationary population in the United States and in other countries to agricultural production trends are evident. Agricultural production during the past century was geared to supply the demands of rapidly increasing populations. Now agricultural producers must recognize the far-reaching effect of reduction in the rate of increase of populations and with it the slowing down of demand for food products.

The spirit of the new civilization is well expressed by Thompson:

> "Industrialism, which for almost a century bade fair to flood the world with people, so that not even its continued advance in efficiency could ensure them a good living, has provided its own cure in making living conditions such that a steadily increasing proportion of people refuse to raise large families. Indeed, many of them refuse to raise children at all."

The fact must not be disregarded, however, that there are in the world, according to the figures compiled by the International Institute of Agriculture, only 13,000 million acres of land available for food production. The likelihood of synthetic foods is very remote. At any rate, synthetic foods would make a poor substitute

for beefsteak. It is also well to keep in mind that the supply of natural resources is not unlimited. The rate at which natural resources have been exploited and wasted is alarming and by no means a credit to humanity. This applies to mineral and plant resources, and especially to the greatest of all natural resources, the soil. Much of agriculture can rightly be classed as soil mining. Vast areas have been ruined for agricultural production by faulty soil management. Want and scarcity have played a great part in the events of human history. Many people, even at this date, are continually on the verge of starvation. Reuter cites a long list of comparatively recent famines and gives estimates of the millions of human lives lost through starvation. While the farmers of the plains of North America were burning corn in 1921, starvation stalked the plains of Russia. The supposed "curse" of surpluses and carry-overs is a recent innovation.

Should the population of the world ever reach 5,200 million, which is not likely for a considerable period of time at present rates of increase, then, keeping in mind that there are but 13,000 million acres of arable land, there would be but 2.5 acres per capita, which is close to the minimum amount of land required for the support of one human being. Agricultural production can be supplemented, of course, by the utilization of sea foods, but the importance of sea foods can be readily overemphasized. Gray *et al.* (6) point out that the amount of land in Germany prior to 1914, after allowances were made for importations of food products, was 2.0 acres per capita.

Optimum Population Density. The problem of determining an "ideal man-land ratio" is fraught with difficulties. Obviously some countries and sections are overpopulated, while others have resources to support larger populations than they now have. Opinions relative to optimum densities differ. Nevertheless, populations show certain rather definite tendencies in reaction to particular resource patterns. The population history in a new country such as the United States is largely a response of population to a most favorable supply of natural resources. Reuter summarizes population tendencies leading to the theoretical optimum in the following manner:

"1. So long as there exists uncultivated fertile areas within a country, a sparse population is unfavorable to the best economic returns.

2. A reasonably dense and increasing population is favorable to occupational specialization, and the consequent rise of intellectual and leisure classes is conducive to progress especially in intellectual, artistic, and other lines not immediately nor primarily productive of utilitarian values.

3. A sparse population, in the presence of undeveloped resources, gives rise to the phenomenon of migration and the consequent mongrelization or displacement of peoples and the cross-fertilization or substitution of cultures.

4. A sparsity of numbers hinders and density favors communication, and communication is the fundamental prerequisite to cultural advance.

5. The welfare of the individual units of a society is closely dependent upon the relation of numbers and the means of subsistence."

The factors determining world centers of population will be discussed in the next chapter.

REFERENCES

1. Bonar, J., *Malthus and His Work.* Allen & Unwin, London, 1885.
2. Bowen, E., *An Hypothesis of Population Growth.* Columbia University Press, New York, 1931.
3. Carr-Saunders, A. M., *The Population Problem.* Clarendon Press, Oxford, 1922.
4. East, E. M., *Mankind at the Crossroads.* Scribner, New York, 1923.
5. Gray, L. C., and O. E. Baker, "Land utilization and the agricultural problem," *U. S. Dept. Agr. Misc. Pub.* 97, 1930.
6. Gray, L. C., O. E. Baker, F. J. Marschner, B. O. Weitz, W. R. Chapline, W. Shepard, and R. Zon, "The utilization of our lands for crops, pasture, and forests," *U. S. Dept. Agr. Yearbook* 1923:415–506.
7. Gregory, H. E., A. G. Keller, and A. L. Bishop, *Physical and Commercial Geography.* Ginn, Boston, 1910.
8. Keller, A. G., *Societal Evolution.* Macmillan, New York, 1931.
9. Malthus, T. R., *An Essay on the Principle of Population.* Ward Lock & Company, London, 1872.
10. Pearl, R., *The Biology of Population Growth.* Knopf, New York, 1925.
11. ———, L. J. Reed, and J. F. Kish. "The logistic curve and the census of 1940," *Science*, N. S. 92:486–488 (1940).
12. Reuter, E. B., *Population Problems.* Lippincott, Philadelphia, 1923.
13. Ross, E. A., *The Changing Chinese.* Century, New York, 1919.
14. Sumner, W. G., and A. G. Keller, *The Science of Society*, Vol. 1. Yale University Press, New Haven, 1927.

15. Sweeney, J. S., *The Natural Increase of Mankind.* Williams & Wilkins, Baltimore, 1926.
16. Thompson, W. S., *Population Problems.* McGraw-Hill, New York, 1930.
17. Wattal, P. K., *The Population Problem in India.* Bennett, Coleman & Company, Bombay, 1916.
18. Willcox, W. F., "The expansion of European population," *Amer. Econ. Rev.*, 5:737–752 (1915).
19. Wissler, C., *Man and Culture,* Crowell, New York, 1923.
20. Wright, H., *Population.* Harcourt, Brace, New York, 1923.
21. Zimmermann, E. W., *World Resources and Industries.* Harper, New York, 1933.

Chapter IV

FACTORS DETERMINING WORLD CENTERS OF POPULATION AND AGRICULTURAL PRODUCTION

The Human Environment. At the beginning of his work on *Political Geography,* Ratzel makes the far-reaching statement: "Jeder Staat ist ein Stück Boden und Menschheit" (every nation is a bit of soil and humanity). The extent to which the development of society, social institutions, and the welfare of the individual human being is influenced by environmental factors has been discussed by numerous authors. Man, of course, can adapt his modes of living and means of gaining a livelihood to quite a variety of climatic and other environmental factors. Yet it cannot be denied that the physical environment sets quite definite limits to practically all lines of endeavor and that particular elements of the environment not infrequently determine the extent to which it may be modified to make a given area more or less habitable and suitable for human occupation. Any given area must either directly or indirectly be able to produce the means by which man may modify the direct effects of his physical environment.

The general relationship of world population to agricultural pursuit and development has been pointed out in the previous chapter; it is the object of this chapter to discuss more directly the factors determining the fitness of a given region for a more or less dense population.

The present population of the world is estimated as somewhat above 2 billion. There are at the present time four very distinct world centers of population, namely (1) western Europe, (2) the eastern temperate part of North America, (3) China and Japan, and (4) India and the East Indies. The first two of these are white centers while the last two represent population centers of colored races. The Caucasian and Mongolian races are the two ruling races. Figure 1, taken from Zimmermann (9), shows the distribution of population over the surface of the earth.

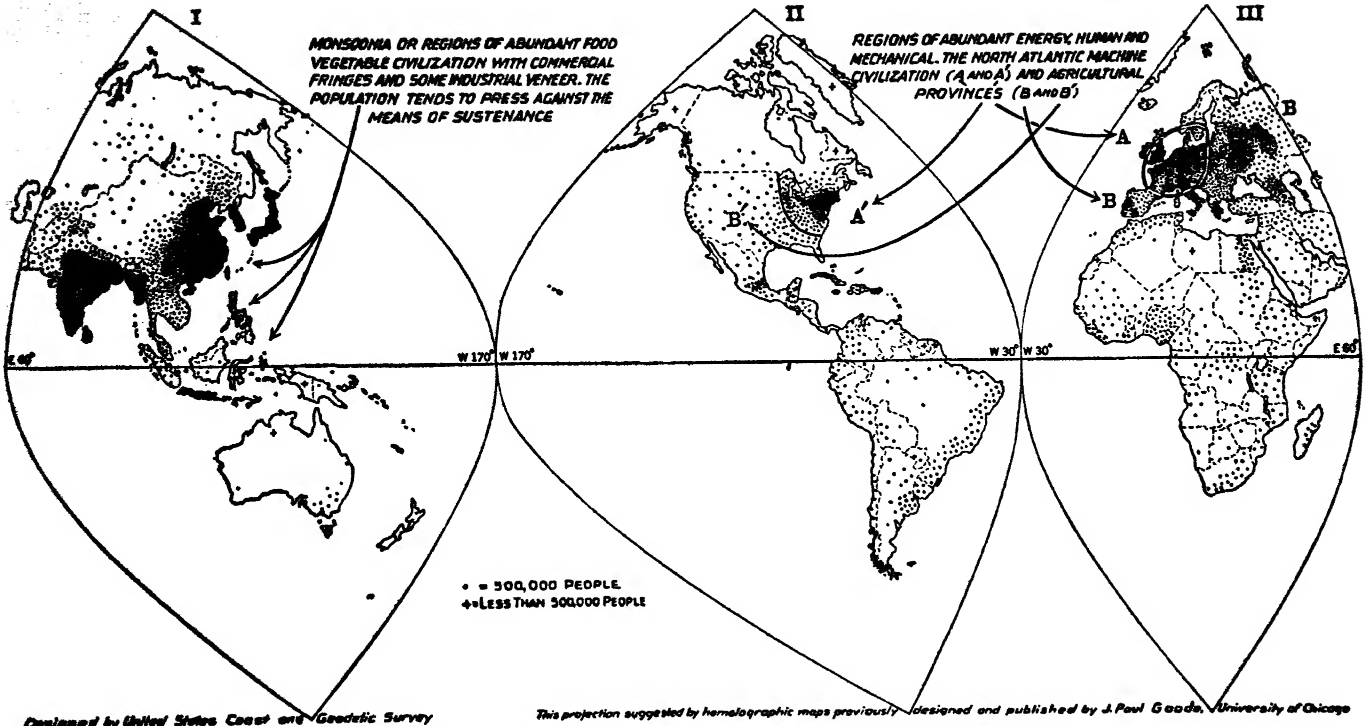


FIG. 1. Distribution of the world's population. (After Zimmermann.)

Potential Centers of World Population. Certain definite factors have been operative in the establishment of the present large centers of population. Other centers, no doubt, will develop in the future in such generally favorable regions as along the western coast of North America, at the southern and especially southeastern tip of Africa, the southeastern part of Australia and New Zealand, and in the more temperate regions of South America. It will be noted that all the probable future centers of population are in regions now occupied by the white race and, therefore, logically may be counted on to be white centers. Since the white race occupies by far the greater expanse of the earth's surface, conditions favorable to its requirements will determine mainly the future of the existing centers of white population as well as the development of potential centers. The areas available to the colored races are already densely populated; great increases in their numbers cannot be expected unless they can muster sufficient force to occupy new areas with environmental conditions favorable for the support of dense populations.

Probably as important as possession to the future of the existing centers of population and to the development of potential centers is that lands now in the possession of the white race are high in climatic energy, well endowed with natural resources, and accessible to world trade. In other words, these areas are quite habitable. Taylor (7) presents maps based on physiographic data which "indicate that white settlement will tend to congregate around five world centers, or cluster of cities of a type which Geddes named conurbations. These are London, Chicago, Sydney, Durban, and Buenos Aires. Of these, the center in the United States will probably be the largest." This prediction is somewhat at variance with the theory of the establishment of stable populations in the near future, as discussed in the previous chapter.

The potential possibilities for the future development of a region, as stated by Olbricht (6), were formerly evaluated mainly on the basis of the fertility of its soil, the amount and distribution of precipitation, its wealth of mineral resources, and above all its accessibility, so essential to economic means of communication. To these factors, states Olbricht, must be added the new bioclimatic factor or the influence of the climatic energy of the region in question. The lack of climatic energy in the Mediterranean type of climate is looked upon by Olbricht as a contributing, if not the most im-

portant, factor in the decay of early centers of civilization of antiquity in the Orient and in the disintegration of the cultures of ancient Greece and Rome. The strength and vigor of populations living in areas of low climatic energy, if they are to be maintained, must be revived continually by an influx of emigrants from areas of high climatic energy. Unless that is possible, a deterioration in energy and a desire for accomplishments, according to Olbricht, is bound to take place.

Advancements in medical knowledge particularly along the lines of disease prevention have been effective in recent years in contributing to the habitability of otherwise uninhabitable areas.

Factors Determining World Centers of Population. Climatic conditions are no doubt of primary importance in determining the distribution of human energy, since the climate of a region determines more than any other single factor, not only the health of a people but also the type and fertility of the soil and its most economic utilization. All the great present and potential centers of population are located in the world's great agricultural regions. Some of them, notably those which Huntington (4) so aptly designated as the rice civilizations, developed in strictly agricultural regions under the impetus of an available and abundant supply of food. Climatic conditions producing good health and an energetic race are essential to the establishment of great and progressive centers of population. The vegetable civilizations of the Far East, notably in China and India, produced and still support great populations. They have developed and continue to survive in regions lacking in climatic energy. These people did not have the energy to progress like the people of northwestern Europe even though their civilization is much older. They clung instead to the old ways and were complacent under existing conditions. The Japanese developed, on the other hand, in a more energetic type of climate and, as evidenced by their activities, are embued with the spirit of progress.

"But," states Taylor, "however energetic a race may be it has not much chance in the struggle for existence if natural resources are wanting." Abundant natural, especially mineral, resources make possible a great concentration of population within limited areas, provided that these areas are readily accessible. The brief survey of the effects of the industrial revolution served to emphasize

the relationship between industrial activities and population increases.

The factors determining density of population are interrelated so that it is difficult to discuss them separately. But man's health and energy depend upon climate and weather more than on any other single factor. It is for this reason that the effects of climatic factors will be considered first. All elements of climate enter into play, *viz.*, temperature, rainfall and humidity, amount of sunlight, air movements, and variability. Each of these factors will be taken up in order insofar as possible.

Temperature. Temperature, as a single factor, is of greatest importance in determining the fitness of a region for human occupation and endeavor. The direct effect of temperature on man is to a great degree modified by other climatic factors. This must be kept in mind when optimum temperatures are discussed. Temperature sensibility (Temperaturgefühl), as Hann (2) designates it, is influenced especially by the humidity of the air, more particularly by the relative humidity. It is affected in a smaller degree by wind velocity and the intensity of the sunlight; these factors, of course, are associated more or less with variations in humidity.

The northern boundary of white settlement corresponds with the northern limits of cereal production, running from the southern part of Alaska across Canada, striking the southern end of Hudson Bay, across Eurasia from the northern portions of Norway and Sweden, across Finland, European Russia, and Siberia to the southern extremity of Kamchatka. This same line also cuts off the southern tip of South America. The polar boundary of agriculture is not far from the annual isotherm of 30°F.

For physical health the optimum temperature for the white race is given by Huntington (4) as around 64°F as an average for day and night together. The optimum for mental labor is given a good deal lower, probably at around 40°F. These figures given by Huntington do not take seasonal variations into consideration. Olbricht also distinguishes between optima for mental and physical energy, giving the points of 4°C (40°F) and 16°C (52°F) for each. Taylor gives the annual optimum temperature best suited for the white race as around 55°F. He classes annual temperatures into groups, in order of their favorable effects, as (1) 50 to 60°F, (2) 40 to 50°F, (3) 60 to 70°F, (4) 30 to 40°F, (5) 70 to 80°F, (6) 20 to

30°F, (7) above 80°F, and lastly (8) below 20°F. Taylor considers the annual isotherm of 70°F as marking the maximum for the growth of the white race. Likewise, dense populations cannot be expected to develop in regions with an annual temperature of less than 40°F. It must be considered that these figures have general application only. They do not take into account the factors influencing temperature sensibility.

Olbricht observes a slower shading off of civilization from the optima in the temperate zones toward the equator than toward the poles. In other words, the tundra of the polar regions are greater enemies to civilization than the rainy tropical forests which, notwithstanding their unfavorable influences, are able to produce plant products.

The classification of regions with regard to prevailing annual temperatures has general application only. The variability of the climate is of considerable importance. The temperature sensibility is also of great consequence and cannot be left out of consideration in the evaluation of temperature belts. Since, however, it is affected by a variety of climatic phenomena, it would be difficult to set up reliable indices. Temperature sensibility is influenced to the greatest degree by the amount of moisture in the air and also by air movements (Visher, 9).

The conditions pointed out by Visher explain why the southwestern portion of the United States and regions with similar climates, with rather high annual and especially high summer temperatures but with relatively low humidities and prevailing winds, are nevertheless quite healthful and well suited for human occupation. Except for these conditions man could not endure without danger or great discomfort the high summer temperatures in regions with extreme continental types of climates.

Likewise, the interior northern regions of the larger continents would be quite unsuitable for human habitation were it not for the low humidity and the comparative calm during the extremely cold winter months. Owing to these conditions of the atmosphere, the prevailing low winter temperatures can be endured without too much discomfort. This refers especially to the continental regions of the northern Great Plains area in the United States, to the prairie provinces of Canada, and to the central areas of Russia, both in Europe and in Asia. While these areas do not at present and cannot

in the future be expected to have dense populations, they are, nevertheless, of great importance from the standpoint of supplying food products, especially cereals, to the world's great population centers. The low humidity of the air makes these regions habitable, but since this low humidity is rather closely correlated, not only with the amounts of precipitation, but also with seasonal variability in the to-be-expected amounts of rainfall, it offers a great obstacle to stable crop production and to the establishment of even moderately dense populations. "Not only are the grasslands on the western border of the plains country in a climatically dry region," states Bowman (1) in speaking of climatic conditions prevailing in eastern Montana, "they are in a climatically variable region. They are in the grip of a general law, that the drier the climate the less dependable the rainfall. It is not true that deserts are always dry. What makes them undesirable for most humans is that one cannot depend upon their being wet." This statement applies to all regions with markedly continental, more specifically grassland, types of climates as does his statement that "the marginal belts of light rainfall, where farming is barely possible, are the regions of greatest agricultural insecurity."

Rainfall and humidity. Rainfall and the humidity of the air in general are, next to temperature, the greatest factors in determining the fitness of a region for human endeavor. The interrelationships of humidity and temperature sensations have already been discussed. Rainfall is unlike temperature in that it is not possible, at least not without stating a considerable number of modifying factors, to determine any optimum amount. Taylor states that the lower limit of important settlement can be placed at about 15 to 20 inches of precipitation per annum. A rainfall of more than 60 inches is generally considered a disadvantage. Taylor sets up a provisional optimum of 50 inches per annum in the construction of his "econograph." This appears fairly high. The effectiveness of precipitation as it relates to plant life is modified by a variety of climatic factors such as temperature, seasonal distribution, and, above all, evaporation. More will be said about this in discussions relating to plant habitats, classification of climates, and studies of particular ecological factors.[1] Since centers of population correspond well with centers of intensive crop production, it is prudent

[1] See Chapter XIII, "Humidity Provinces."

at least to mention these various interrelationships at this point. A high temperature during the rainy season in regions with well-defined seasonal precipitation, as in Japan, is objectionable. A combination of high humidity and high temperatures is decidedly unhealthful. On the other hand, heavy precipitation during the cooler seasons of the year, as in the Pacific Northwest, is not nearly so objectionable.

Variability. The other climatic factor of importance in determining the suitability of a region for the development of dense populations is variability or variation in weather. This refers to seasonal as well as to intraseasonal variations. As pointed out by Huntington (3) and Olbricht (6) the greatest climatic energy is found in regions with frequent cyclonic disturbances, such as in northwestern Europe around the North Sea and the Baltic, northeastern and central United States, the southeastern portion of Canada, and at the southeastern tip of Australia. Huntington (3 and 4) and Huntington and Cushing (5) present numerous maps showing interrelationships of climatic energy and various measures of degrees of civilization. The region of greatest climatic energy in the United States and Canada is interrupted to the west by an area with long summer heat and drought, and to the south by higher than optimum temperatures and lack of variation during the summer months. The climate along the Pacific coast is not considered variable enough to be classed by Huntington among the most energetic. The same objection is made to the climate of the Mediterranean region. The belt of greatest climatic energy in Europe extends over the region adjacent to the northern Atlantic, the North Sea, and the Baltic, where cyclonic storms are common. Climatic energy decreases as the unbroken plains of Poland and Russia with their long monotonous winters are encountered.

It is in these regions of greatest climatic energy that the greatest advances in civilization have been made. It is also in the regions of greatest climatic energy that the excess of human energy has frequently been spent in destructive wars.

Resources. Centers of population are not determined by climatic factors alone. If that were the case, they would have to be self-supporting, which they are not. Present centers of population are based on an exchange economy. Because of their extreme concen-

tration of population in limited areas, such centers must draw on distant areas for their food and other supplies.

It is fortunate for the development of centers of population that the regions of highest climatic energy and the regions with the greatest wealth of natural resources are coincident, or nearly so. The natural resources which come into play here are fertile soils; minerals; a source of power and heat, such as coal, oil, and water power; timber products; returns from fisheries; etc. The development of a manufacturing center demands the presence of raw products to be converted into finished goods, the power necessary to accomplish this economically, accessibility to trade channels, the necessary capital to finance the undertakings, and last, but not least, the necessary labor to man the factories. Where a source of power and the required raw materials are available, the other requirements will be forthcoming, providing, of course, that the location is favored by accessibility and that there is a demand for the product or products to be manufactured.

Taylor, after considering the close relationship between the abundance of coal and the density of populations, made the far-reaching statement that "the more one studies the resources of the world the more astounding is the position of the United States. That country is most highly favored in respect to temperature, rainfall, coal — so that the center of the world's industry and of the white population will inevitably move across the Atlantic from Europe to North America." The significance of this statement is evident, though to one agriculturally minded and recognizing that populations must above all be fed, it is difficult to see why the Australian geographer does not include the wide expanses of fertile soils on the North American continent in his enumeration of great natural resources.

Space does not permit the discussion of other natural resources influencing population densities. Hydroelectric power and power from petroleum products may be expected to replace coal at least in part and in certain locations. A good illustration of the substitution of hydroelectric power for coal is found in the highly centralized industrial development in parts of Norway and Sweden.

Soil fertility. That the fertility and the producing capacity of the soil has a great influence on the density of population that a region can support is shown by the fact that the most densely

populated areas of the world are located in regions where soil and climatic conditions are generally favorable to the growth of crop plants. A fertile soil, together with climatic conditions favorable to an abundant growth of plant life, is essential to the development of a dense population in regions where vegetable civilizations predominate. The phenomenally dense populations of such regions as southeastern China, eastern India, and Java owe their existence almost entirely to the fertility and producing capacity of the soils in those areas. Industrial civilizations are not so directly dependent on native soil fertility as are the vegetable civilizations. They produce manufactured goods that can be exchanged for food and other necessities of life. But since their food and clothing come from the soil, expanses of fertile soil are, nevertheless, a great asset to industrial centers. Large expanses of fertile soil are essential to agricultural development. Progressive agricultural regions contribute very directly to the growth of industry. Not only does agriculture supply many of the raw products to be processed; it also provides an outlet for a wide variety of manufactured articles. No industrial region can develop and prosper without a source of raw materials or a market able and willing to utilize the articles manufactured. The western movement of the center of population in the United States can be attributed largely to the extensive and progressive agricultural development of the lands of the Mississippi Valley and the eastern Great Plains area.

Some of the world centers of population, notably those of the industrial sections of northwestern Europe, are not located in areas with high native soil fertility. The soils contiguous to these population centers have, however, been brought up to a high producing capacity through the expenditure of human energy and the application of scientific methods of soil management. Agriculture in the sandy lowlands of Germany and in similar sections was given a great impetus through the intelligent application of potassium salts and other commercial fertilizers. In other places vast sums have been expended for drainage and other forms of improvement. Though one thinks of white centers of population as highly industrialized, which they are, a rather high percentage of the inhabitants of those areas gain their livelihood directly from the soil.

The Econograph. Taylor points out four factors determining the establishment of centers of white population, namely (1) tem-

perature, (2) rainfall, (3) coal reserves, and (4) the average elevation of the region, which reflects on accessibility and ease of communication within the area in question. Of these factors the least weight is given to the last, the elevation factor. On the basis of these four factors Taylor constructs a quadrangular graph which he calls the "econograph." The four determining factors are graphed on the axes of the figure. An optimum econograph is presented in Fig. 2. Taylor considers 55°F the optimum annual temperature and 50 inches of rainfall per annum as most favorable. The most favorable location is taken at near sea level. The coal supply is graphed in units of 10,000 tons per square mile. The maximum area of the econograph is 1,000 units. Lines connecting regions of equal econograph area, to indicate equal habitability, are designated as "isoiketes." Taylor gives the theoretical isoiketes for Europe. The values of these isoiketes correspond well with the location of the great centers of population in that the isoikete 600 embraces the great industrial areas of the continent. The econograph is of value also from the standpoint of variations in its shape in that it reflects directly on the utilization of the area in question, that is, whether the area is primarily suited to some form of agriculture or to the development of industry. Where the area is suited to both, a symmetrical graph results.

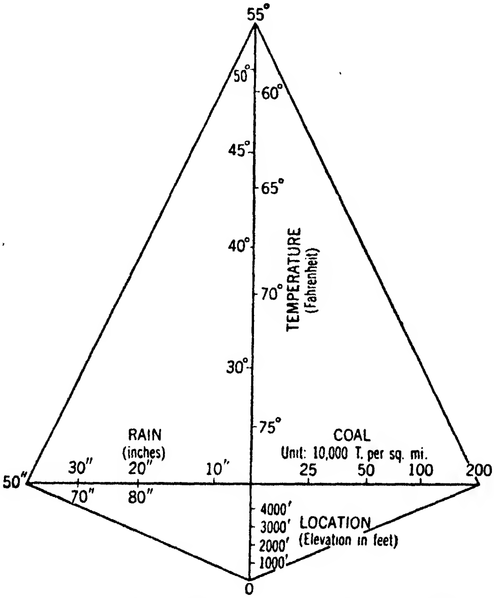


Fig. 2. An optimum econograph. (After Taylor.)

Population Centers and Food Producing Areas. After discussing centers of population it will be interesting to consider briefly the relationship of these centers to the world's important food producing areas. As has been pointed out before, the distribution of any specific crop is determined by physiological and social factors

that need not be discussed here. It is well, however, to call attention to the fact that, in order to make possible the intensive production of food and other agricultural products, climatic conditions must be healthful to the people engaged in agriculture. Furthermore, most of the great staple crops used by the white race are grown to best advantage in those regions now largely occupied by this race and under climatic conditions favorable to white civilization. There are, of course, notable exceptions to this, as for instance, the production of sugar from sugar cane, the production of rice, and some of the world's cotton producing areas. In order to include the world's great food producing areas it is necessary to add to the four great centers of population but a few other areas, some of which were spoken of as potential centers of population. Ten rather well-defined important world agricultural areas can be pointed out as: (1) the central portion of the United States and the prairie provinces of Canada; (2) Argentina and southern Brazil; (3) northwestern Europe; (4) central and southern Russia; (5) the Balkan area; (6) the Mediterranean region; (7) China and Japan; (8) India; (9) southern Africa; and (10) southeastern Australia. The limiting factors to crop production in each of these areas will be discussed in Chapter VIII, which deals with the physiological limits of production.

The factors of location and accessibility apply to centers of production as well as to centers of population. This is true especially for the production of products for export. New agricultural regions, as in South America and in the interior of Asia, can be brought into production by making them accessible to world commerce. For more than a century Russia has attempted to secure a seaport on the Mediterranean so that her excess products could move out while her northern harbors are frozen. Russia has become involved in two major European wars in an effort to realize this objective.

REFERENCES

1. Bowman, I., "Jordan country," *Geog. Rev.*, 21:22–55 (1931).
2. Hann, J., *Handbuch der Klimatologie*, Vol. 1. Verlag von J. Engelhorn, Stuttgart, 1908.
3. Huntington, E., *Civilization and Climate.* Yale University Press, New Haven, 1915.
4. ———, *The Human Habitat.* Van Nostrand, New York, 1927.

5. Huntington, E., and S. W. Cushing, *Principles of Human Geography.* Wiley, New York, 1924.
6. Olbricht, K., *Klima und Entwicklung. Versuch einer Bioklimatik des Menschen und der Säugetiere.* Gustav Fischer, Jena, 1923.
7. Taylor, G., "The distribution of future white settlement. A world survey based on physiographic data," *Geog. Rev.*, 12:375–402 (1922).
8. Visher, S. S., *Climatic Laws.* Wiley, New York, 1924.
9. Zimmermann, E. W., *World Resources and Industries.* Harper, New York, 1933.

Chapter V

THE SOCIAL ENVIRONMENT

Environment Defined. The terms "environment" and "habitat" may be used interchangeably; they refer to one and the same thing. Both terms were used originally in the sense of describing the particular locus inhabited by an organism or group of organisms. With the advance of scientific methods, the ecologist is not entirely satisfied with a mere description of the places inhabited by organisms but aims rather to evaluate definitely the conditions under which living beings exist and survive. The application of the word "habitat," in relation to plant life, for that reason has been extended to mean, as Tansley (16) speaks of it, "the sum total of effective conditions under which a plant or community lives." Fitting (4) has the same conception of the environment, speaking of it (Standort) as "die Gesamtheit der Umweltsfaktoren eines Organismus." Nichols (11) defines the term in the same manner as Tansley and Fitting but stresses the response of the individual organism to environmental factors by stating that "the environment of any organism may be described as the sum total, or perhaps better, the resultant of all the external conditions which act upon it."

This chapter will be devoted to an evaluation of some of the factors of the social environment of crop plants; the physiological environment and its components will be discussed in the following chapter. Since, however, the two have such a direct bearing on crop distribution, it will not be possible always to keep them entirely apart; they are so closely related that certain phases of one cannot be considered without bringing in the other.

The Physiological and Social Environments. The distribution of crop plants, as has been pointed out in Chapter I, is determined not only by physiological, but also by economic and social factors. The physiological growth requirements of any crop plant set definite limits to the production of that particular crop.

The social environment, as is evident from its definition, includes a great variety of factors. The distribution of crop plants is influenced by many economic and social forces; consequently, the field to be considered under the social environment cannot well be circumscribed. Obviously the various factors of this social environment cannot all be treated in detail in a general publication; volumes could be and have been devoted to discussions of each phase of this great problem. The entire field of economics has a more or less direct bearing on the problem of crop distribution. Cardon (3) assigns to the field of agricultural economics a coordinating position in relation to other lines of agricultural research. The economics of production may not set quite so definite a limit to the production of a certain crop as the physiological requirements of that crop, but, nevertheless, it determines the eventual limits of production. A crop cannot survive for any great length of time in a given area unless its production represents a profitable enterprise. As stated by Hughes and Henson (6), "the major crop of most sections is a high profit crop for that section."

The need of differentiating between the physiological and the social environments, in relation to the general study of crop distribution, is brought out by the comprehensive definition of land as given by Black and Black (1). These authors not only include in their definition the nature-given surface of the earth and the materials comprising this surface but recognize also the importance of the prevailing climatic conditions, its location with respect to markets, and any alteration of the surface instituted by man during his use or improvement of the land.

Natural and Artificial Social Environments. World trade is based on the exchange of commodities and services. Since the production of goods can be stimulated or retarded by various economic and political devices, it becomes necessary to differentiate between natural and artificial environments. Where a production enterprise is developed and survives on its own merit without the aid or interference of definitely superimposed economic or political stimulation or inhibition, it may be considered as existing and surviving in a natural environment. An artificial environment is created by the establishment of various forms of subsidies or in some cases possible inhibitions to production. Import duties, tariffs, and import quotas offer the most notable examples of the creation of

artificial social environments. Such subsidies may be considered as economic or man-made barriers to the free movement and indirectly to the production of goods.

The world-wide operation of the principle of comparative advantage to the production of any commodity is definitely interfered with by the creation of such economic or political barriers. It enables producers to grow certain crops in areas where soil and climatic or other conditions are not altogether favorable to their production. Since prices are elevated to an artificial level, it encourages also the employment of a higher intensity of production than would otherwise be possible. It goes without saying that artificial environments are created at the expense of the consumer of the products so produced. Likewise, the height of the barriers created depends upon such factors as the docility of the consumer, the degree of economic stress prevailing, and not infrequently the creation and fostering of a spirit of intense nationalism by various agencies. That the erection of man-made barriers influences the normal or the to-be-expected world-wide distribution of field crops on the basis of their physiological growth requirements is self-evident. The producers of commodities protected by subsidies are placed in an artificial environment and at an advantage over those producers operating in unprotected regions. Unless climatic and soil conditions in competing areas are comparatively so much superior as to overcome the effects of these man-created barriers erected by normally importing countries, or countries where the physiological environment may not be especially favorable to the production of the crop in question, the production of the crop will increase in response to the creation of the artificial social environment at the expense of areas in countries with favorable climatic and soil conditions for the production of the crop, but where the production of that crop is not subsidized.

How import duties and the establishment of import quotas affect the world market of agricultural commodities has already been pointed out in Chapter I. Natural barriers set definite and constant limits to production, while artificially created barriers are subject to rapid revisions depending on changes in political and economic moods.

A word of caution is necessary in discussing the operation of the principle of comparative advantage, in that factors other than those

of the physiological environments of competing regions have a direct bearing on the subject. Differences in the social environments and, above all, differences in the standards of living of various regions may have profound effects. The production of spices, drugs, and perfume plants may be cited as an example. Climatic and soil conditions in many sections of the United States are favorable to the production of these specialized plants but, until the crises brought about by the second World War, not at a price to compete with foreign products. The greatest item of cost in the production of such crops consists of labor. In enterprises demanding great amounts of hand labor, a country with high labor costs cannot compete with those of low labor costs and low standards of living.

Agricultural Areas in Relation to Population and Transportation. Von Thuenen represented agricultural production zones surrounding a center of population located on a fertile unbroken plain, without navigable rivers or any means of communication except by wagon, by concentric circles drawn around the city. Zone 1 produces products that are both bulky and highly perishable. Zone 2 produces less perishable and less bulky products such as potatoes or milk. In the third zone the milk is made into butter, a product still less bulky. Farther out, grain crops are fed to livestock and transported on the hoof. Finally comes the range.

Figure 3 gives a graphical view of the transformation of the production zones occasioned by introducing a ready means of transportation such as a navigable river. Modern city markets represent a more or less exaggerated form of von Thuenen's graphic presentation. Every means of transportation, by water, by rail, or by paved highways, entering a city or group of cities creates bulges in the surrounding production zones.

With the introduction of refrigeration, even more or less perishable agricultural commodities can be moved over great distances. Nevertheless, the distance over which a commodity can be moved economically is in proportion to its value and bulk. Prairie hay can be moved but short distances before the equivalent of its value is expended for transportation costs, while alfalfa hay, because of its greater value per unit, can be moved economically over greater distances. Likewise, the coarse grains like oats and barley, unless they are intended for some special use, cannot be moved economically over as great distances as wheat or flax, which are of greater

unit value. Wheat, because of its value and special use, moves over great distances from its numerous points of production to milling and consuming centers.

The production zones of any crop are shaped also by the physiological limitations encountered. Furthermore, the methods of

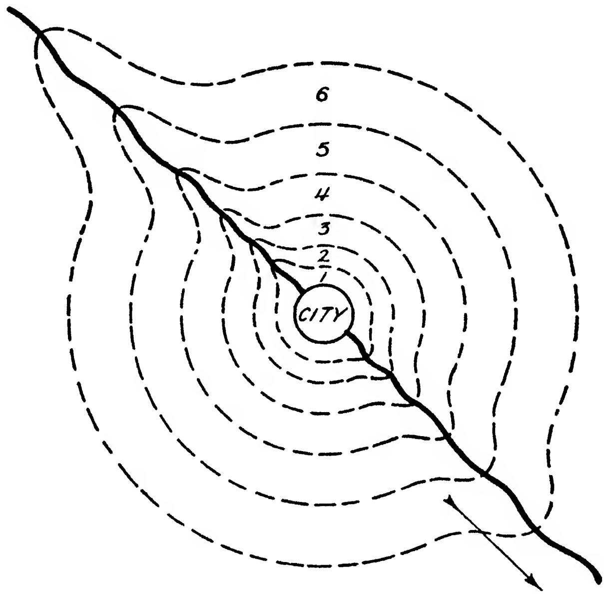


FIG. 3. Zones of production surrounding a city on a plain, with a river flowing through it. (Adapted from Von Thuenen.)

production employed may be modified materially by variations in existing economic, climatic, and soil conditions in various areas. Differences will be found in the degree of specialization in production, in the amount of power machinery employed, and in the intensity of production.

A good illustration of the effects of definite agronomic, economic, social, distribution, and transportation factors on the development and continuance of the main large milling centers of the United States is given by Pickett and Vaile (13). Space does not permit the discussion of these various phases as they influence the milling industry. They are mentioned to bring out the fact that the production zones and the industries they supply with raw products to be processed are influenced by a great variety of factors.

Transportation as a Factor in Interregional Competition. The cost of moving a commodity to market has a very direct bearing on the possibilities of deriving profit from any production enterprise. The greater the cost of transportation the more remunerative must be the enterprise in order to survive. Not infrequently the greater transportation costs from distant producing areas are in part counterbalanced by other factors of the social environment or by more favorable conditions of the physiological environment. If that is not the case, or if environmental factors are even less favorable at the points distant from the market than near it, the enterprise is at a considerable disadvantage. Under such conditions expansions in production can and do take place only during periods of comparatively high prices, to be followed by painful retractions upon the return of prices to more normal levels.

Lower transportation costs have the same effect as the moving of an area of production, if that were possible, nearer to the market. Such a condition would serve to put the more distant producing centers in a more advantageous competitive position with those areas near the terminal markets. It might even call for major adjustments in the sections near the market. Change in any other factor, such as the more extensive employment of power machinery, which might lead to a lower cost of production in one or another section would have similar effects.

It must be borne in mind that transportation costs do not always vary directly with the distance over which commodities must be moved. Land transportation, especially where mountain ranges or other physical barriers are encountered, is notoriously more expensive than water transportation. The development of crop producing areas of such great importance in the world commerce of agricultural commodities as those in South America, notably Argentina, in Australia, and in southern Africa, was greatly furthered by their fortunate location with respect to cheap water transportation. The fortunate location of these distant areas (distant, that is, from the world's main centers of population) with respect to trade routes by water enables them to compete actively with those areas located near the great markets of the world.

As stated by Gregory *et al.* (5),

"the wealth of a country cannot be utilized to the greatest advantage unless there are good transportation facilities; our great iron and steel

industries would still be in their infancy, were it not for the excellently organized service afforded by the transportation companies on the Great Lakes. The great wealth in our farm lands in the central West would still be unavailable, were it not for the railways which connect those regions with the seaboard."

Before the advent of truck transportation and the subsequent improvement of highways, production of even the less bulky products was out of the question in areas without railroad facilities. The perfection of automobiles, trucks, and tractors has had material influences on local production. These various devices for travel, transportation, and motive power have established what Bowman (2) quite aptly terms a "gasoline culture."

Technological Advances through the Improvement of Crops. Very marked improvements in nearly all commercially important crop plants have been made through the efforts of plant breeders. Improvements have been made not only along the line of increasing yielding capacity but also in developing crops of required market characteristics.

Table 2, taken from Klages (7), shows the secular trends in the yields of the major grain crops in the states of the Mississippi Valley over a 37-year period 1891–1927, inclusive. Since the slope of the trend lines of the annual average yields, fitted by the method of least squares, is positive in most instances, the trends shown point to increased yields over the 37-year period of the study. The highest annual increment shown by any crop was for corn in Iowa, namely, 0.285 bushel per acre annually. Wallace (17) reports an annual increase of 0.25 bushel in Iowa corn yields from 1891 to 1919. Reed (14) found an annual increase of 0.283 bushel per acre in the years 1890–1926, while Mattice (10) reports an annual increment of 0.486 bushel of corn per acre for the state of Iowa for the period 1901–1925. The introduction of hybrid corn in recent years has resulted in still greater increases in yields.

These increases in unit crop yields cannot be ascribed altogether to activities in the improvement of crops; improvements have also been made in methods of tilling and managing the soil on which the crops are grown. A permanent system of agricultural production concerned above all with the preservation of the fertility of the soil or with the actual improvement of the soil, however, is not so readily or generally adopted by producers as are new and improved

varieties of crop plants. Much of American agriculture, as pointed out before, can be classified rightfully and unfortunately as a system of mining soil fertility. How long that may go on is not the question here. The point is that crop yields have increased in spite of this condition. And it may be stated that the improvement in crop plants has counterbalanced in part the effects of trends toward lower yields induced by soil depletion and depreciation. This statement is not made to infer that all producers allow their soils to depreciate. Prevailing economic conditions not infrequently may determine the effectiveness or the feasibility of establishing a permanent system of agricultural production. The direct effect of crop-improvement work is well illustrated by the comparative performance of two varieties of hard red spring wheat at three South Dakota stations, Brookings, Highmore, and Eureka. Klages (8) showed that Ceres, the new variety, over a five-year period of comparison at these three South Dakota stations yielded respectively 23.8, 36.1, and 10.3 per cent more than Marquis, the older established variety which was being replaced.

TABLE 2. ANNUAL INCREMENTS IN THE YIELDS OF CORN, OATS, WHEAT, BARLEY, AND RYE IN THE STATES OF THE MISSISSIPPI VALLEY, AS INDICATED BY THE SLOPE OF THE TREND LINES OF YIELDS AS FITTED BY THE METHOD OF LEAST SQUARES FOR THE 37-YEAR PERIOD 1891–1927, INCLUSIVE

States, Arranged from East to West	*Yields*				
	Corn	Oats	Wheat	Barley	Rye
Michigan	+ 0.128	+ 0.138	+ 0.133	+ 0.126	+ 0.006
Wisconsin	+ 0.267	+ 0.243	+ 0.169	+ 0.153	+ 0.021
Minnesota	+ 0.259	+ 0.100	− 0.017	− 0.003	− 0.050
North Dakota	+ 0.100	+ 0.138	− 0.092	− 0.100	− 0.151
South Dakota	+ 0.203	+ 0.155	+ 0.018	+ 0.029	+ 0.038
Ohio	+ 0.254	+ 0.157	+ 0.099	+ 0.073	+ 0.004
Indiana	+ 0.158	+ 0.103	+ 0.091	+ 0.081	− 0.022
Illinois	+ 0.094	+ 0.105	+ 0.087	+ 0.248	− 0.007
Iowa	+ 0.285*	+ 0.222	+ 0.178	+ 0.200	+ 0.023
Nebraska	+ 0.015	+ 0.138	+ 0.080	+ 0.122	+ 0.027
Kentucky	+ 0.069	+ 0.044	+ 0.019	+ 0.184	− 0.005
Missouri	+ 0.001	+ 0.079	+ 0.034	+ 0.187	− 0.037
Kansas	− 0.118	+ 0.062	+ 0.002	− 0.022	+ 0.032

* The figure 0.048 as published in *Ecology* was wrong and is hereby corrected to read 0.285.

The greatest advances in the breeding of crop plants have been made in providing producers with varieties or strains able to overcome, in part if not in entirety, certain limiting factors in crop production, such as varieties resistant to certain diseases, varieties resistant to lodging, and the early-maturing varieties. The development of early-maturing varieties of crop plants has had the direct effect of increasing the acreage to be devoted to these crops in northern areas or in increasing the yields in areas especially adapted to them.

Technological advances through improvements in soil management. Great advances have been made in the management of crop production enterprises. Reference is made here to improvements in handling the details of production with special reference to soil management.

It is a recognized fact that a type of cropping tending toward a permanent system of agriculture and an improvement in the soil is more easily inaugurated in regions with an abundant supply of moisture, where conditions are favorable to the establishment and growth of legumes, than in moisture-deficient areas where either the production of legumes is altogether out of the question or they can be established only in seasons with more than the normal amount of rainfall. Humid regions are more suited to the development of diversified systems of cropping and a general diversification of all agricultural enterprises, while the more hazardous and extensive one-crop systems tend to prevail in the drier areas. The yields of crops in sections with an abundance of moisture, if natural fertility is lacking, can be increased greatly by the application of either barnyard manure or commercial fertilizers, or both. In dry areas the addition of fertilizers will not increase yields materially except in those occasional seasons when the moisture supply is great enough to allow plants to utilize the extra elements of nutrition supplied them.

A comparison of humid and subhumid regions will show that the fertility of the soil in humid areas can be maintained more readily and that producers there have at their command a greater variety of devices for increasing and stabilizing production than do producers in the latter areas, where the trend is toward extensive rather than intensive systems of production. From a competitive standpoint, the extensive systems of production of the subhumid

areas, while returning lower and more uncertain yields, enable producers to utilize power machinery to a greater extent, thereby reducing costs of production, than is possible in the areas with the more diversified and intensive systems of agriculture. The permanency of agricultural production in some of the dry areas of the frontier fringe, however, remains to be demonstrated.

Technological advances through the development of power machinery. The direct effects of the development and employment of power machinery in agricultural production have been mentioned in Chapter II. At this point the effect of this development on inter-regional competition is to be considered. The one great influence of the rapid adaptation of power equipment to agricultural production has been the movement of crop areas into the drier and, strictly from a climatological standpoint, less favorable areas. Large unbroken areas ideally adapted to extensive systems of farming with power machinery have been brought into production. The production of wheat and cotton has been especially influenced by these developments. From a competitive standpoint it is necessary to consider first the relative costs of production in the new and in the older producing areas.

Recent expansions, at least expansions following the first World War, of crop acreages, notably those of wheat and of cotton, have been into the more arid sections. This happened not only in the United States but also in other wheat producing countries. The expansion of crop acreages due to the creation of artificial social environments is not considered at this point. That the feasibility of continued extensive production by the employment of power equipment is yet to be demonstrated in many of the drier areas with erratic types of climates is a well-recognized fact. No attempt is made here to evaluate the hazards of production in those areas; that will be left to another chapter. It is enough to say that the employment of such power equipment as the tractor, the combine, and the truck has brought a lot of land into production, and in many instances the costs of production have been lowered.

One very pertinent fact must not be overlooked. While it is true that cereal crops in many localities may be sown more cheaply and harvested more cheaply by the employment of the most modern types of power machinery than by means of horse-drawn equipment, it is also true that in order to harvest a crop it is first neces-

sary to produce one. Even the most modern mechanical methods of tillage cannot produce the moisture so essential to the growing of a crop. The fact cannot be denied that the main limiting factor to crop production in subhumid or semiarid sections, whichever name is selected, is a lack of a sufficient and reliable supply of moisture in a high percentage of the growing seasons. Low-cost production is not possible unless fair to good yields are obtained. The employment of no amount of power equipment can eliminate the powerful check imposed by this limiting factor.

It is hardly fair to draw an analogy between agricultural production and a mining enterprise, as was done by Nourse (12) in the following paragraph.

> "If the changes in technique which are now upon us prove to be as revolutionary a character as has been suggested in the present chapter, the result would apparently be to alter permanently the schemes of valuation in different agricultural sections, which were built up under the older traditions of American farming. From the immemorial past, the predominance of hand-labor methods in farming has given great differential superiority to those well-watered and fertile lands which showed the greatest capacity to absorb large amounts of human toil. But much as in the field of mining the progress of scientific metallurgy and heavy power machinery have made profitable the utilization of low-grade ores, so the development of scientific and machine agriculture have brought into cultivation considerable areas of formerly submarginal land, and have indeed put a premium upon extensive methods of utilizing lighter soils in the remoter agricultural areas, and regions of scanty rainfall. Profits are being found by going rapidly over large areas of comparatively low-yield land, and the scarcity value of lands in the older sections has quite possibly lessened as a result. Their differential superiority has shrunk under the new technique, and market values must ultimately establish themselves in the light of this fact."

While it is true that agricultural production will and must be modified in the older areas as a result of competitive influences from the lands newly brought into production, it is also true that an expansion into the "areas of formerly submarginal lands" is not infrequently a hazardous undertaking. If agriculture can be maintained in these areas only by means of successive governmental grants and aids, then agricultural production proceeds in an artificial social environment, an environment created at public expense and to the detriment of the older, more stable agricultural sections

of the country. Furthermore, coming back to the analogy between agricultural production and mining, there is one great difference between these two enterprises which makes an analogy between the two imperfect. The yield of the refined product that will be obtained from working over any given ore can be determined by chemical means before the initiation of mining operations, while this is by no means the case in agricultural production, where the yields to be obtained are determined to such a high degree by the vicissitudes of the climate. This applies especially to attempts at agricultural production in areas with highly variable and erratic climates or where lack of moisture is a limiting factor. The timely employment of heavy power equipment aids in the conservation of moisture. Moisture, however, can be conserved only when and where it is present. Agriculture, as will be pointed out presently, can and does modify its methods of production in response to variations in climatic and economic conditions; yet it cannot be denied that favorable soil and climatic conditions remain the basis of a prosperous and well-balanced agriculture.

The Intensity of Production. Agricultural production obeys the law of diminishing returns. That is, for every successive unit of labor or capital applied per unit of area there will not result an equal and proportionate return. Only a given amount of labor, seed, fertilizer, etc. can be applied to any given area of land with an expectation of increasing the net return. The relationship between expenditures and net, rather than gross, return is the all-important consideration in deciding whether or not a given production enterprise can survive under a given set of economic and physiographic conditions.

Space does not permit the discussion of all phases of the application of the law of diminishing returns to agricultural production. Only the main factors affecting the optimum intensity for returns in different regions and under varied soil conditions can be considered.

Intensive systems, that is, systems using liberal amounts of capital and labor per unit of area, prevail in densely populated areas whose soil and climatic conditions are generally favorable to agricultural production, while extensive systems are the rule in sparsely populated regions, especially if the climatic conditions are not favorable to the attainment of high average yields.

Krzymowski (9) gives an interesting discussion of the various problems relating to the intensity of agricultural production. His paper has an especial appeal to students who may be mathematically inclined, since it goes in detail into the mathematics forming the foundation of von Thuenen's theory of intensity. Attention is given to both gross and net returns and to the factors influencing the point of most favorable degree of intensity for greatest net return under a variety of conditions.

Agricultural production has been and still is going through a process of adapting the size of individual holdings to prevailing climatic, soil, and economic conditions. Spafford (15) showed the relationship of moisture and soil conditions to size of farms from the eastern to the western Great Plains area. As the lower rainfall portions in the central and western parts of this great area are approached, the size of the individual holdings definitely increases. Likewise, regions with poor soils in this area have larger farms than those blessed with better soils.

Changes and trends in economic conditions have a great and very direct effect on the optimum degree of intensity to be applied to the individual farm for the production of a maximum net return. Likewise, major economic changes demand regional adjustments in production programs. These adjustments can be made as far as existing climatic and soil conditions allow. Nature is dynamic; crop producing areas, as the past has shown, may shift in response to a great variety of factors of the physiological and social environments.

REFERENCES

1. Black, J. D., and A. G. Black, *Production Organization.* Holt, New York, 1929.
2. Bowman, I., "Jordan country," *Geog. Rev.*, 21:22–55 (1931).
3. Cardon, P. V., "Relating research in agricultural economics to other fields of agricultural science," *Jour. Farm Econ.*, 16:189–199 (1934).
4. Fitting, H., *Aufgaben und Ziele einer vergleichenden Physiologie auf geographischer Grundlage.* Verlag von Gustav Fischer, Jena, 1922.
5. Gregory, H. E., A. G. Keller, and A. L. Bishop, *Physical and Commercial Geography.* Ginn, Boston, 1910.
6. Hughes, H. D., and E. R. Henson, *Crop Production.* Macmillan, New York, 1930.

7. Klages, K. H. W., "Geographical distribution of variability in the yields of field crops in the states of the Mississippi Valley," *Ecology*, 11: 293–306 (1930).
8. ———, "Small grain and flax varieties in South Dakota," *S. Dak. Agr. Exp. Sta. Bull.* 291, 1934.
9. Krzymowski, R., "Graphische Darstellung der Thuenenschen Intensitätstheorie," *Fühlings Landw. Zeit*, 69:201–219 (1920). (A translation of this paper is presented by P. G. Minneman in *Jour. Farm Econ.*, 10:461–482 (1928).)
10. Mattice, W. A., "Weather and corn yields," *Mo. Wea. Rev.*, 59:105–112 (1931).
11. Nichols, G. E., "The terrestrial environment in its relation to plant life," in *Organic Adaptation to Environment*, M. R. Thorpe, ed., Chap. 1, pp. 1–43. Yale University Press, New Haven, 1924.
12. Nourse, E. G., *Agriculture, Recent Economic Changes in the United States*, vol. 2, pp. 547–602. McGraw-Hill, New York, 1929.
13. Pickett, V. G., and R. S. Vaile, "The decline of Northwestern flour milling," *Univ. of Minn. Studies in Economics and Business*, No. 5. University of Minnesota Press, Minneapolis, 1933.
14. Reed, C. D., "Weather and corn maturity in Iowa," *Mo. Wea. Rev.*, 55:485–488 (1927).
15. Spafford, R. R., "Farm types in Nebraska as determined by climatic, soil, and economic factors," *Nebr. Agr. Exp. Sta. Res. Bull.* 15, 1919.
16. Tansley, A. G., *Practical Plant Ecology*. Allen and Unwin, London, 1926.
17. Wallace, H. A., "Mathematical inquiry into the effects of weather on corn yields in eight corn-belt states," *Mo. Wea. Rev.*, 48:439–446 (1920).

PART II

THE PHYSIOLOGICAL ENVIRONMENT OF CROP PLANTS

Chapter VI

THE PHYSIOLOGICAL ENVIRONMENT

Primary Importance of the Physiological Environment. "Life is able to proceed, then, in any particular plant, only so long as the external conditions do not surpass the physiological limits of the life processes of the form considered" (Livingston and Shreve, 10). That the distribution of crop plants is determined by the combined influence of physiological, economic, social, technological, and historic forces has been stated on several occasions. It is well to keep that in mind at all times. Obviously, however, no crop plant can attain a place of importance in the cropping system of any given locality unless it exhibits a certain degree of adaptation to the external conditions prevailing in that locality. Some of the factors involved in the study of adaptation will be taken up in detail in a later chapter. In this chapter the general and broad relationships of plants to their physiological environments will be discussed without consideration of causal relationships.

Habitat. The terms "environment" and "habitat" may be used interchangeably. They both refer to one and the same thing, namely, to the sum total of all external conditions affecting the development, special responses, and the growth of plants. Since the term "habitat" was first used by botanists, and especially by ecologists, it is best to apply it to the description of the physiological conditions influencing the distribution and growth of plants as contrasted with the social environment which deals with the influence of a variety of factors other than those concerned with the direct growth requirements determining the distribution of crop plants.

Actual and Potential Habitats. It has been stated that "no two spots on the face of this earth have exactly the same climate." While such a statement may be true when the various components of the climate are examined in their minutest detail, it also is a recognized fact that regions with similar climates tend to exhibit similar life forms. This does not mean that the identical species

necessarily will be represented or predominate in remote regions with similar climates but only that certain sets of climatic conditions will lead to the development of certain types of climax vegetations or a corresponding physiognomy. Certain species may be excluded from distant regions, not because conditions there are not suited to their growth, but simply because the spread of such species may have been prevented by various kinds of barriers. If once introduced, by artificial or normal means, they may spread rapidly in the new area. The introduction of European weeds and grasses in America and other areas of the world offers a good example of this phenomenon. It is well, therefore, to recognize an actual and a potential habitat of plants.

Plants may have either a wide or a narrow range of adaptation. That is, they may be very exacting in their requirements of the environment and therefore be limited in their distribution; or they may have a great tolerance to factors either working in excess or lacking in intensity. The distribution of some crop plants may be limited, not because of this condition, but because conditions were adverse to migration. The distribution of the sorghums was greatly furthered by man's taking a part in aiding their migration. This was true also with such important cultivated plants as corn, wheat, potatoes, tobacco, and to some degree all plants since they became objects of world trade. It would be difficult to visualize the present agriculture of the Great Plains area of the United States without such important introduced crop plants as hard red winter wheat, hard red spring wheat, durum wheat, the sorghums, and alfalfa. The production program is centered largely around these important crops which exhibit a remarkable degree of adaptation to the prevailing environmental conditions. Much of agronomic experimental work in the last analysis is a test designed to find the limits of the potential habitat of crop plants.

Attempts to grow crop plants beyond the limits of their potential habitats have resulted in great losses to private enterprise as well as in great damage to the public domain. Many of the marginal lands of humid regions for their best utilization should have been allowed to retain their natural vegetation rather than to have been put under cultivation. High, often abnormal, prices of agricultural products prevailing for but short periods played a prominent part in divesting such marginal lands of their natural protective cover-

ings. In semiarid regions lands either too shallow, too light, or lacking in permeability sufficient for the storage of moisture in the past years have been broken up with no regard for the future. Such lands were often cultivated but for a short time, until it became evident that crops could not be grown on them with profit; they were then allowed to lie idle and to waste away. Lands approaching the limits of the potential habitat should not be devoted to the production of crop plants. The natural vegetation such as timber or grass will yield better and more certain returns, at least until the time when they may be forced into the production of specialized crops by economic demand.

Factors of the Habitat. Livingston and Shreve criticize the usual classification of habitat factors from the standpoint that they are largely based on "origin or source, rather than according to their mode of physically affecting the plant." While classifications of habitat factors may not, and are not expected to, explain the very complex relationships of a plant during its various phases of development to its also changing environment as a growing season progresses, nevertheless, they may be of great help to the student in arriving at some conception regarding the processes involved. Most of the investigations dealing with the many reactions of the plant with environmental factors of necessity have been descriptive rather than quantitative. With increasing refinements in methods available to investigators, more and more exacting quantitative work may be expected. But, for the time being, many investigations will continue to be descriptive in nature.

Livingston and Shreve point out that progress is being made by means of refined laboratory methods toward obtaining more definite knowledge of the relationships of a plant to environmental factors, but that "a large amount of laboratory experimentation of the most refined physical sort will be required before we shall ever approach an adequate knowledge of the influence of single conditions upon plants, the far more difficult study of the complex environmental systems of which these single conditions are always components has already begun to attract attention."

Fitting (5) calls attention to the fact that the behavior of plants can be explained only when investigations regarding such behavior are actually conducted in their natural environments. Unless this is done the reactions studied may be pathological rather than

physiological in nature. Geographical and ecological physiology can be expected to provide the basis of information for the study of plant and crop geography upon a physiological basis as fostered by the monumental work of Schimper (12).

Livingston and Shreve classify the environmental conditions that are most influential in the determination of plant development and distribution as: (*a*) moisture conditions; (*b*) temperature conditions; (*c*) light conditions; (*d*) chemical conditions; and (*e*) mechanical conditions. Tansley (17) throws the factors of the habitat

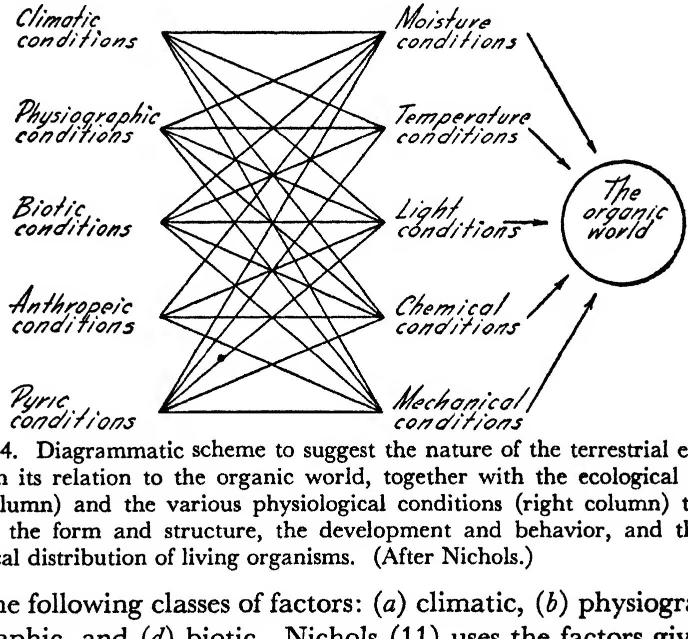


FIG. 4. Diagrammatic scheme to suggest the nature of the terrestrial environment in its relation to the organic world, together with the ecological sources (left column) and the various physiological conditions (right column) that influence the form and structure, the development and behavior, and the geographical distribution of living organisms. (After Nichols.)

into the following classes of factors: (*a*) climatic, (*b*) physiographic, (*c*) edaphic, and (*d*) biotic. Nichols (11) uses the factors given by Livingston and Shreve and by Tansley and adds the anthropeic, the activities of man, and the pyric conditions, the effects and results of the action of fire. Nichols considers the edaphic factors as given by Tansley under the class of physiographic conditions. Figure 4, taken from Nichols, gives an interesting diagrammatic presentation of the nature and the interrelationships of the various factors of the habitat on the organic world. Figure 4 not only lists the various outstanding factors but also shows how they react upon one another. The various ecological factors of the environment will be discussed separately and in detail as they relate to the distribution of crop plants.

The climatic factor of the environment. The climatic factors are many. Since their effects are interrelated, the influences of any specific factor must be considered in the light of the others. The main climatic factors are temperature, moisture, and light; of less importance are atmospheric pressure and air currents. Superimposed on these but not of less importance is periodicity.

The interpretation of climatic data necessitates a knowledge of seasonal variations. Information on the periodicity of climatic phenomena at times or in certain regions may be of far greater value than mere averages. A section may have a high annual rainfall, yet be quite dry at a time of year when plants may be in special need of moisture. Or the average temperature of a region may be neither too high nor too low but at times may exceed a maximum or drop below a certain minimum and thus limit plant production or at least modify the cropping system to be adopted.

Chilcott (1), in his investigations on "The relations between crop yields and precipitation in the Great Plains area," came to the conclusion that "notwithstanding the fact that annual precipitation is a vital factor in determining crop yield, it is seldom if ever the dominant factor; but the limitation of crop yield is most frequently due to the operation of one or of several inhibiting factors other than shortage of rainfall." This conclusion brings out the fact that the specific influences of the various climatic forces are interrelated. The investigations on which this far-reaching statement is based may be criticized from the standpoint that no attention was given to the economy of water utilization by the crop plants discussed. This is a vital factor and should be taken into consideration; moisture, for instance, that falls on the ground only to run off rapidly in the extremely heavy rains quite common in the southern Great Plains area cannot be expected to be of benefit to plant life. Not all moisture falling into a rain gauge produces favorable plant responses.

Periodic climatic manifestations leave a lasting impression on natural vegetation and in like degree have a great influence on the selection of crop plants. As brought out by Hildebrandt (6), uniform climates are conducive to the production of perennial plants, while climates with periodic changes give rise to annual plants. In the tropics uniformly high temperatures make continuous growth possible except under conditions where a period of drought may

throw the plants into a period of dormancy. Perennial forage plants predominate in regions where there is sufficient moisture for the vegetative parts to live over from year to year. In the arid and semiarid sections many plants are able to take advantage of the fact that seeds are less susceptible to unfavorable climatic conditions than vegetative organs; consequently, the plants found either are annuals or are protected from damage during periods of extreme drought by special morphological, structural, or physiological characteristics.

The influence of periodicity of climatic factors especially with regard to moisture has a decided effect on crop distribution. As pointed out by Klages (9), perennial crop plants such as meadow grasses and legumes predominate in regions with a comparatively uniform distribution of rainfall. Most of the forage plants grown in the eastern humid part of the United States, such as timothy, redtop, and the clovers, are perennials requiring relatively abundant supplies of moisture. In the northern Great Plains area a larger number of annual forage plants, such as millets, sudan grass, and early varieties of sorghums, are encountered. In the southern Great Plains area annual plants assume even a greater importance than in the north. The reasons for this distribution are quite apparent in the light of what has been said. Alfalfa, though the dominant forage crop of the western states, is limited primarily to irrigated regions. Alfalfa and sweet clover are also grown extensively in the annual forage area of the Great Plains region. Because of its unusually extensive root system, alfalfa is able to capitalize on the subsoil moisture out of reach of ordinary field crops. As brought out by the works of Duley (3) in eastern Kansas and Kiesselbach *et al.* (7) in eastern Nebraska, the yields of alfalfa declined rapidly after four or five years of growth on land that had not previously been cropped to it. These decreases in yields corresponded to definite decreases and eventual depletion of the available subsoil moisture. A considerable number of years may elapse before the subsoil moisture in subhumid areas may again come up to its original point after once being exhausted. High yields of alfalfa cannot be expected until moisture again becomes available in the lower levels of the soil.

The physiographic factor of the environment. The physiographic factors may be classified as (*a*) the nature of the geologic

strata, (*b*) the topography, and (*c*) the altitude. The soil, or the so-called edaphic factor, will be discussed separately.

In relation to soil formation, the nature of the geologic strata may be considered as an edaphic factor. It is a physiographic factor insofar as it is active in accounting for a given topography. Geologists in the past have attributed too much importance to the nature of the underlying parent rock material with regard to soil formation. While the original material from which soil is formed is of importance, it must be recognized that identical parent rock under varying climatic conditions will give rise to soils of greatly differing physical and chemical properties (Shantz and Marbut, 13).

Topography is a great factor in determining climate. General topography, direction of main mountain ranges to prevailing winds, is important from the standpoint of determining precipitation. Together with the nature of the geological strata, it is a factor in determining the natural drainage of a region.

The slope and exposure of given areas is highly important in the production of certain crops. A southern exposure is warm in the northern hemisphere and desirable for the production of early crops. Yet in areas of limited rainfall such slopes are undesirable. Because of the higher surface temperature and the resulting greater loss of moisture by means of increased transpiration, they often are too droughty for profitable crop production. Good air drainage is essential to the production of tender crops in all regions, especially in high altitudes where there may be danger of frost damage, even in the cereal crops. Precautions against soil erosion must be taken on lands with excessive slopes. The effect of slope on the rate of erosion, as shown by the works of Dickson (2) and Duley and Miller (4), is greatly modified by a variety of factors such as the nature of the soil, the type of cropping, and the intensity of the rainfall.

Topography has a great influence on local climate. It may serve to protect an area from excessive evaporation and may modify the temperature. Klages (8) gives the rates of evaporation as recorded by Livingston's cup atmometers at five different locations in central Oklahoma, showing how such rates of evaporation correlate with plant responses.

More attention will be given in another chapter to the general relationship of topography and altitude to climatic variations. It is sufficient to summarize here the interactions of climatic and

physiographic factors by using the words of Nichols, "The nature of the environment of any locality is determined primarily by the combined influence of climatic and physiographic factors."

The edaphic factor of the environment. It is unnecessary at this point to go into detail on the relationship of various soil conditions such as texture, structure, aeration, reaction, and chemical makeup to various phases of crop production. The edaphic factors (taken from the Greek "edaphos," meaning "the ground") are not static but subject to continual change. The modifications produced may be slow, proceeding in an orderly fashion as in the slow disintegration of the parent rock or the slow removal of soluble elements either by plants or by leaching; again, they may be precipitous, as in certain phases of erosion. But, as aptly stated by Tarr and Martin (18), the soil is the basis of agriculture.

While the bulk of the material making up the soil is inert matter, a soil must always be considered in its three general phases, namely, the physical, the chemical, and the biological. The interactions of these various phases make it very complex.

The soil is one of the most important factors of the habitat. This is true especially in studies limited to a given locus as are most of the investigations of the agronomist. Climatic factors are spoken of as being regional, while the soil factors are local in effect. As Spafford (16) speaks of it, "Soil effects are often submerged by climate." Schimper speaks of climatic and edaphic formations; Tansley [taken from Waterman (19)] criticizes the term "climatic formations" from the standpoint that "Nothing like a sharp line can be drawn between one climatic region and another so that it becomes impossible to delimit climatic formations." While it is true that one type of vegetation gradually shades into another without a distinct boundary between them, it is also true that the climates of the world may be grouped into a relatively small number of classes each of which affects large regions. Within such larger regions soil variations play a prominent part in determining the agricultural utilization of particular areas.

The habitats of two plants in the same field may differ markedly because of soil and physiographic factors. Within a given climatic region the local climate may be modified to a small degree, as brought out by Smith (14 and 15), by the joint effects of edaphic and physiographic factors.

The biotic factor of the environment. It has been said that nature abhors a pure population of organisms almost as much as a vacuum. Pure cultures of plants, as well as of other organisms, are very much the exception rather than the rule. Under the biotic factors are considered the effects of other plants or animals on the particular plant or animal studied. The associates of a habitat may be helpful, neutral, or harmful; there are symbiotic as well as parasitic relationships. In limiting this phase of the discussion to crop plants, the effects of the wanted plants and of the unwanted associates — weeds — and the effects of parasites and of animals must be considered.

The agronomist deals with natural and with man-created associations. The various growth requirements, qualities, and characteristics of the separate plants used in compounding a pasture or meadow mixture must be taken into account if maximum returns are to be expected. Young clover or alfalfa plants growing with a companion crop, not infrequently called a nurse crop, are living in quite a different environment than plants of the same species grown in pure cultures or in competition with various weeds.

Crop rotations and systems of annual cropping involve numerous biotic relationships. In certain areas, as in the drier sections of the Great Plains area, corn in itself may not be a very profitable crop, but it is of considerable value to and results in material increases in the yields of subsequent cereal crops. The survival of disease producing organisms from year to year involves a definite biotic relationship demanding that the same crop or group of crops affected by the same causal organism not be grown too frequently or at too frequent intervals in the rotation. Likewise the reaction of plants to insect injuries involves biotic relationships.

The anthropeic factor of the environment. Man has produced profound changes in plant environments. The various factors discussed in the previous chapter on the social environment have a direct bearing and may again be mentioned at this point. That is hardly necessary. The introduction of grazing animals and of various exotic plants leaves lasting impressions.

The pyric factor of the environment. The action of fire produces great changes, especially in the environment of natural vegetations, and in addition leaves lasting impressions on the soil.

The Time Element and the Habitat. A plant may be characterized, as by Livingston and Shreve, by its "powers or capabilities to respond to stimuli." It must also be recognized that plants pass through rather well-defined and definite phases in the course of their development. The responses to environmental complexes differ materially during these different phases. A wheat seedling demands for maximum development quite a different environment than a flowering or ripening plant. Not only is it necessary to consider the various separate factors but it is equally important to investigate and consider the effects of the duration of the component factors or the time interval in which plants may be exposed to certain stimuli. An exposure to a high temperature for a short interval may result in no lasting detrimental effects, while a longer exposure to a lower temperature under some conditions may lead to death. More will be said about the time factor in the discussion of adaptation and during the course of the consideration of plant responses to various ecological factors. But, since no summary review of plant habitats can be considered at all complete without giving attention to the time factor, it has been very briefly referred to at this point.

REFERENCES

1. Chilcott, E. C., "The relations between crop yields and precipitation in the Great Plains Area," *U. S. D. A. Misc. Circ.* 81, 1927.
2. Dickson, R. E., "The results and significance of the Spur (Texas) runoff and erosion experiments," *Jour. Amer. Soc. Agron.*, 21:415–422 (1929).
3. Duley, F. L., "The effect of alfalfa on soil moisture," *Jour. Amer. Soc. Agron.*, 21:224–231 (1929).
4. ———, and M. F. Miller, "Erosion and surface runoff under different soil conditions," *Mo. Agr. Exp. Sta. Res. Bull.* 63, 1923.
5. Fitting, H., *Aufgabe und Ziele einer vergleichender Physiologie auf geographischer Grundlage.* Verlag von Gustav Fischer, Jena, 1922.
6. Hildebrandt, F., "Die Lebensdauer und Vegetationsweise der Pflanzen, ihre Uhrsachen und Entwicklung," *Englers Bot. Jahrb.*, 2:51–134 (1882).
7. Kiesselbach, T. A., J. C. Russel, and A. Anderson, "The significance of subsoil moisture in alfalfa production," *Jour. Amer. Soc. Agron.*, 21:241–268 (1929).

8. Klages, K. H. W., "Crop ecology and ecological crop geography in the agronomic curriculum," *Jour. Amer. Soc. Agron.*, 20:336–353(1928).
9. ———, "Comparative ranges of adaptation of species of cultivated grasses and legumes in Oklahoma," *Jour. Amer. Soc. Agron.*, 21:201–223 (1929).
10. Livingston, B. E., and F. Shreve, *The Distribution of Vegetation in the United States, as Related to Climatic Conditions.* Carnegie Institution Pub. 284, Washington, 1921.
11. Nichols, G. E., "The Terrestrial Environment in Its Relation to Plant Life," in *Organic Adaptation to Environment*, M. R. Thorpe, ed., Chap. 1, pp. 1–43. Yale University Press, New Haven, 1924.
12. Schimper, A. F. W., *Plant Geography upon a Physiological Basis.* Clarendon Press, Oxford, 1903.
13. Shantz, A. L., and C. F. Marbut, *The Vegetation and Soils of Africa.* National Research Council and the American Geographical Society, New York, 1923.
14. Smith, A., "A contribution to the study of interrelations between the temperature of the soil and of the atmosphere and a new type of thermometer for such study," *Soil Science*, 22:447–458 (1926).
15. ———, "Effect of local influences in modifying the general atmospheric conditions," *Soil Science*, 23:363–376 (1927).
16. Spafford, R. R., "Farm types in Nebraska, as determined by climatic, soil and economic factors," *Nebr. Res. Bull.* 15, 1919.
17. Tansley, A. G., *Practical Plant Ecology.* Dodd, Mead, New York, 1923.
18. Tarr, R. S., and L. Martin, *College Physiography.* Macmillan, New York, 1915.
19. Waterman, W. G., "Development of plant communities of the sand ridge region of Michigan," *Bot. Gaz.*, 74:1–31 (1922).

Chapter VII

EXTERNAL FACTORS IN RELATION TO DEVELOPMENT

External and Internal Factors in Their Relation to Development. The many interesting and not infrequently perplexing problems encountered in studies pertaining to development and adaptation are fittingly introduced by a portion of the first paragraph found in Morgan's (34) volume *Evolution and Adaptation.*

> "Between an organism and its environment there takes place a constant interchange of energy and material. This, in general, is also true of all bodies whether living or lifeless; but in the living organism this is a peculiar one; first because the plant or animal is so constructed that it is suited to a particular set of physical conditions, and, second, because it may so respond to a change in the outer world that it further adjusts itself to changing conditions, *i.e.*, the response may be such a kind that it better insures the existence of the individual, or of the race. The two ideas contained in the foregoing statement cover, in a general way, what we mean by adaptation of living things."

The external factors under which an organism develops provide no doubt the direct stimuli for the various responses. Yet the extent of the responses that an organism is capable of exhibiting are limited by definite internal factors. Under such a broad term as "the internal factors" may be considered the hereditary factors, or the genetic constitution of the individual, the various physico-chemical occurrences within the plant, and the general physiological limitations imposed on all organisms. The first of these will be treated, as it reflects on the problem in hand, in this chapter. The physiological factors will be taken up in a subsequent chapter.

The various interactions between the internal, more specifically the hereditary, factors and the constellation of external factors under which the plant develops are complex.

The influence of external factors on the development of plants and animals has long been recognized. The rediscovery of Mendel's

law toward the end of the last century did much to lead discussion and research toward the internal factors concerning and determining the course of development and the characteristics of the individual organism. Nearly all investigators were soon convinced that neither the internal nor the external factors alone were active in ontogeny. It is quite obvious then that arguments as to whether the one set of factors or the other is of greater importance are of no avail; both are necessary. The genetic constitution of the organism is vital to the ultimate form and characteristics produced. They could not be produced except by interaction with the factors of the environment.

Ontogeny and Phylogeny. Ontogeny, the development of the individual, cannot be considered in detail without attention to phylogeny, the history of the race. The two work together; one must be considered in the light of the other. As Conklin (5) states it,

> "ontogeny and phylogeny are not wholly distinct phenomena, but are only two aspects of the one general process of organic development. The evolution of races and of species is sufficiently rare and unfamiliar to attract much attention and serious thought; while the development of an individual is a phenomenon of such universal occurrence that it is taken as a matter of course by most people, something so evident that it seems to require no explanation; but familiarity with the fact of development does not remove the mystery which lies back of it, though it may make plain many of the processes concerned."

The agronomist, the plant breeder in particular, is concerned far more with races and varieties or even with physiological strains of crop plants than with species. As brought out by Werneck (43), "agricultural phenology takes as its lowest unit the race or variety of cultivated plants in their area of agricultural distribution." The interest of the agronomist also extends to uncultivated species of crop plants as sources of needed genetic characters for crop improvement purposes. Thus *Triticum timopheevi* is being used as a source of resistance to major wheat diseases, wild species of *Solanum* are of value in potato breeding.

Investigators during the truly descriptive period of biology, especially of zoology and more particularly of embryology, dealt with both the internal and external factors concerned in development. It is beyond the scope of this chapter to discuss in detail the preformation view as contrasted with the theory of epigenesis.

The adherents of the first view attached special importance to and overemphasized the internal factors of development. The propounders of the preformation theory assumed development to consist simply of the unfolding and enlarging of what was present already in the germ. Such a theory of "emboitement" or "infinite encasement" would give the external factors of the environment little or no opportunity to take part or to become instrumental in the molding of the characteristics of the organism. While Harvey's epigram "omne vivum ex ovo" has found abundant confirmation, it has been found also that external factors have a profound influence and that they cannot be disregarded. Under strict adherence to the preformation theory it would be difficult to account for progressive evolution. Furthermore, adaptation, direct or indirect, would be difficult to explain.

The Units of Heredity and Development. A detailed discussion of the units of inheritance, genes, is rather out of place here; nevertheless, these units are definitely involved in development and for that reason merit some attention. It is difficult to give a clear-cut definition of the term "gene" without becoming involved in a detailed discussion of the behavior of somatic characters in inheritance.

The terms "factor" and "gene" are used interchangeably in the literature. Some writers make no differentiation between the terms "factor" and "determiner." Coulter (7), however, advocates the restriction of the use of the term "determiner" to cases where but one hereditary unit is involved in the production of a character. He uses the term "factor" in cases where two or more units interact in the production of a character. Johannsen (19) considers the genes as hereditary germinal units that may sometimes need to combine to produce a visible somatic character. Babcock and Clausen (1) speak of the gene as "an internal condition or element of the hereditary material upon which some morphological or physiological condition of the organism is dependent." Frost (13) gives two distinct meanings as to the term gene: (*a*) a definite physical unit of segregation, and (*b*) a developmental potentiality. East (11) states, "the regularity with which characters occur in breeding experiments justifies the use of a notation in which theoretical factors or genes, located in the germ cells, replace the actual somatic characters."

McGee (31) makes the point that "the career of the organism, as individual species or as a larger group, may be considered as the resultant of two forces, (*a*) the initial or directing force operating through heredity, and (*b*) the secondary or modifying force operating through interaction with the environment. Neither one nor the other of these forces is of greater importance to development." As stated by Lefevre (28), "every organic individual is the product of two sets of conditions both of which contribute to the sum-total of its qualities." He continues, "the organism, then, as we see it, is the product of constant interaction between internal and external conditions, and if either of these factors is varied, a difference in the result is observed." Likewise, Haecker (17) brings out that investigators of Mendelian inheritance are confronted constantly by a great obstacle in that it is necessary to deal always with two sets of variables, the visible external factors and the invisible hypothetical units of heredity of the germ plasm. There is a constant interaction between these two factors, and, while progress is being made, a complete analysis of the nature of this highly complex interaction has not yet been made. Numerous hypotheses as to its nature have been put forth from time to time.

Most of the early workers, in their attempts to describe or to explain the nature of the units or, perhaps better stated, the "something" connected with the phenomena observed in heredity, undervalued the influence of external conditions on the course of development. This was the case with Darwin's "provisional hypothesis of pangenesis" and with Weismann's elaborate theory with its biophores, determinants, ids, and idants. As stated by Sharp (42), "for Weismann . . . development (ontogenesis) was definitely bound up with the evolution or unfolding of a complex contained in the fertilized egg. Although he did not hold that the units of the egg have the same spatial relations as their corresponding characters or structures in the adult, it has been said with some degree of truth that he transferred preformation to the nucleus."

Herbert Spencer made provisions for his "physiological units," formulated as a material conception of heredity, to be influenced by external circumstances in that variation in the environment could induce slight changes during the process of their multiplication. De Vries (9), in his theory of "intracellular pangenesis," also

paid considerable attention to the effects of external conditions. These early theories of development and differentiation can no longer be adhered to; yet it is interesting to note that these early investigators were aware of the effects of the external factors of the environment.

One more factor must be mentioned relative to the inheritance of quantitative characters. Here the environment plays a very important part. The plant breeder in selecting from the progeny of hybrids attempts to isolate genotypes with the largest possible number of favorable characters. The environment plays a prominent part in enabling full expression of the various genotypes of the segregating population. It is highly desirable in such cases to have favorable climatic and soil conditions so that the genetic constitution of the population under observation is found within the limit of physiological expression.

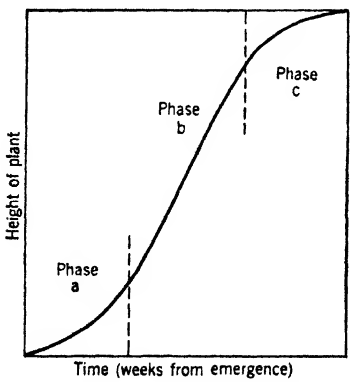


FIG. 5. The growth curve constructed by plotting successive height on the ordinate against time on the abscissa.

The Course of Growth in Plants. The various responses of plants to the external factors of the environment may well be studied and observed by the various modifications called forth by these factors in the course of growth and in the growth habits of plants. The course of growth and development in plants may be presented graphically by means of growth curves based on either the successive weights or heights or on periodic increments. These increments may be given as actual increases over a previous measurement, as proportionate increases, or may be placed on a percentage basis. The growth curve based on successive measurements of mass, given on the ordinate, plotted against time, on the abscissa, can be used to good advantage and gives perhaps a better and more workable interpretation than any other method to the various activities summarized under the general term "growth." When the growth curve is presented in this fashion, a logarithmetic curve, shown in Fig. 5, results. Whether or not the curve is smooth and symmetrical depends entirely on the environmental conditions under which the plant may happen to grow.

The various conceptions of growth — whether it consists of increase in size, volume, bulk, or a change in form — may be summarized by the statement that growth is evidenced by an increase in size or bulk accompanied by changes in form resulting from an excess of assimilation over disassimilation.

Growth curves of plants may be presented either on the basis of successive weights, or, since there is a close correlation between weight and height, they may be constructed on the basis of successive height measurements taken at stated intervals. The author has on numerous occasions found the value of *r* for correlations of height of green plants with the dry weights of such plants to be 0.90 or higher. It is a decided advantage to base the successive measurements required on the same plants. When successive plant weights are relied upon as a measure of rate of growth, it is necessary, of course, to make use of different individuals for each weighing and dry-weight determination. Such procedure, unless based on large numbers, adds materially to the magnitude of the experimental error. Since the dry-matter content of plants varies greatly from youth to age and with changes in growing conditions, the use of green weights as an index of activity is out of the question.

Priestley and Pearsall (36), in their study of the rate of increase in the number of yeast cells, point out three phases in the course of the growth curve. These three phases are also in evidence in the growth curves of plants. They are marked *a*, *b*, and *c* in Fig. 5. These phases may be readily detected in symmetrical curves produced under normal growing conditions. They are not so outstanding under highly abnormal climatic conditions with their erratic plant responses.

In relating the above to plant activities it is but necessary to point out that the plant is relatively most active during the initial stages of growth, that is, during phase *a*. The increase in mass during this phase is an exponential function of time. The percentage activity is high; a high percentage of the cells are actively engaged in the process of division. The amount of material actually assimilated is not large. This is due, not to the lack of activity, but to the small size of the plant. The activities of the plant during this stage may be compared to those of a small factory working at a high rate of speed in a most efficient manner. The output is small

not because of lack of activity but because of the size of the establishment or factory.

During phase *b* of the curve, the rate of growth is more or less proportional to time. The relative activity is not so high as in the initial phase, but the number of cells engaged in active assimilation is large, and materials are rapidly accumulated. This phase has been designated as the grand period of growth. During this phase an ever-increasing number of cells is required for supportive structures, reserve materials, etc.; the number of plant cells actively engaged in the processes of active growth is constantly being reduced. Growth during this phase may be compared to the activities of a large factory with a large output, with the magnitude of the output accounted for rather by the size than by the rate of activity of the plant.

The final, *c* phase of the growth curve is characterized by a rapid falling off of the rate of activity and the eventual suspension of growth. The main processes during this phase are concerned with the translocation and the fixing of materials previously assimilated rather than with the assimilation of new materials.

The growth cycles of plants with determinate and indeterminate habits of growth differ. They are both affected and definitely respond to environmental factors. In the former, the end-point is more pronounced and definite than in the latter. In other words, the inherent characteristics of these two types of plants respond differently to environmental factors; in plants with indeterminate habits the final point may not be reached until either climatic or soil conditions become unfavorable to further activity while the formation and maturity of the seeds mark the end of the growth cycle of plants with the determinate habit.

Mathematical Formulation of Growth Curves. It is beyond the scope of this chapter to attempt even a brief summary of the numerous equations that have been advanced by various workers on growth and rates of growth in plants and animals. Gaines and Nevens (14) suggest the possibilities of making use of the constant *K* of Robertson's growth equation. Robertson (38) made use of the equation expressing the course of an autocatalytic monomolecular reaction in formulating his growth curves. His equation in its simplest form, that is, upon integration, is expressed in the following formula:

$\text{Log} \frac{X}{A - X} = K\,(t - t_1)$, in which X = the growth (height or weight) which has been attained in time t; A = the total amount of growth attained during the cycle; K = a constant, the magnitude of which determines the general slope of the curve; and t_1 = the time at which growth is half completed, the number of days required for the plant to attain half of its final growth. Rippel (37) shows graphically how the slopes of growth curves of plants are affected by variations in the magnitude of K. The slopes of the curves increase with increases in the values of the constant.

Klages (21) reports that an analysis of the growth curves of cereals grown in field plats may yield information of value to supplement performance data from such plat experiments, especially since such curves may provide an index on the basis of which the different seasons encountered during the course of the experiment may be evaluated and compared. Annual growth curves of cereals were analyzed from the standpoints of symmetry shown, maximum height attained, and interval of time from emergence to the attainment of maximum height on the basis of the generalized or average slopes of the curves produced. Attempts were made to evaluate the slopes of the growth curves by the employment of Robertson's equations. It was found, however, that the differences in the calculated values of K (the constant) in any variety fluctuated so widely for the different values of t (the time factor) that but little significance could be attached to the average of the separate values of K for the different values of t. This was the case especially when the curves deviated greatly from the symmetrical. The fitting of the growth data to straight-line trends by the method of least squares gave the most reliable and workable means of expressing the general slope of growth curves of crop plants grown under field conditions.

Brody (3) gives a very complete summary of the various mathematical attempts at the formulation of growth curves. There is a certain fascination in the appearance and employment of smooth and regular curves even though such curves are the exception rather than the rule in natural phenomena. Beautiful symmetrical curves more often result when plants are grown under controlled laboratory conditions than when the plants are grown under the more variable conditions found in the field. It is exceedingly difficult to clothe with the dignity of a mathematical formula the rather

unsymmetrical growth curves produced when plants are exposed to the various favorable and unfavorable factors of the environment.

That the slopes and shapes of growth curves are directly influenced by environmental factors is to be expected. A growth curve may be regarded as a graphic summary of the many and complex plant activities culminating in the building up of plant reserves and associated with continual change in form. Variations from the normal growth requirements find expression in the form of the growth curves produced. During abnormal or erratic seasons very irregular and unsymmetrical curves defying mathematical formulation result. The reaction of plants to a variety of environmental conditions can frequently be studied by means of the modifications produced by these environmental factors on their respective growth curves. The cause of these deviations from the regular and to-be-expected course of development not infrequently make up interesting and important problems for the agronomist and ecologist. There is no doubt that numerous growth equations developed and used by different investigators have been of value to particular lines of research. It is well to keep in mind, however, that the numerous processes concerned in organic growth are too complex to yield in all cases to a single master equation.

Rhythm in Development. Plants in their course of development pass through a series of orderly and consecutive stages. As Scharfetter (39) states it, "plants pass through an annual stage of diffusion during which they undergo development in foliage, blossom and fruitage followed by a period of repose." As already pointed out, this course of orderly development is determined by both the internal, inherent characteristics of the plant and by the external, environmental factors under which development and growth proceed. The constant recurrence of environmental factors from season to season plays an important part in regulating the course of development of plants adapted to certain environments so that they fit into such environments. Obviously, the development of an annual plant from emergence to maturity is one of continuity; the first phase in the process is essential to the ones to follow.

The course of development of cereals may be illustrated by an outline of the phases of the growth cycle. Since fall-sown cereals pass through a period adverse to growth, their courses of development will differ from those of the spring-sown grains which are not

forced by environmental factors to pass through a resting period. The classification, given below, of the various phases of the course of development for fall- and spring-sown cereals has been adopted with slight modifications from Schmidt's (41) outline.

Fall-Sown Cereals	*Spring-Sown Cereals*
1. Germination and emergence	1. Germination and emergence
2. Fall tillering	2. Tillering
3. Vegetative rest	3. Jointing
4. Vegetative awakening and spring tillering	4. Flowering
5. Jointing	5. Maturity
6. Flowering	
7. Maturity	

Each of the above phases may be subdivided as the nature of the investigation to be conducted may demand. Thus, under germination may be considered various phases such as the initial period, concerned largely with the imbibition of water; the period of rapid chemical changes within the embryo and endosperm; the rupture of the seed coat; the appearance of the plumule, coleorhiza, and primary roots; and finally emergence. The early vegetative phases may be designated at first by the number of leaves formed and later by the number of stools, or tillers, produced. The jointing stage is characterized by a rapid increase in the height and weight of the plant and by the emergence of the inflorescence out of the boot. The flowering phase is of interest from the standpoint of the time when fertilization actually takes place, whether before the emergence of the head out of the boot, as usually is the case in barley, or after complete emergence, as in rye or wheat. The final phase may be subdivided into the milk, the soft-dough, the hard-dough, the ripe, and the dead-ripe stages. The first stages up to the flowering and heading period are conveniently referred to as the vegetative phases, while the postheading phases are not infrequently designated as the sexual phases of development. The time intervals of the different stages are subject to wide variations; they are influenced not only by the inherent characteristics of the plant but also by a great variety of climatic, nutritional, and special relationships.

Since development is orderly, continuous, and definitely associated with seasonal advance and progressive changes in the climatic factors, it has been appropriately designated as rhythmic.

The general course of development in plants may well be designated as by Scharfetter as the "vegetation rhythm." Often it is convenient to present the vegetation rhythm graphically. Since growth may be regarded as the summation or the end product of all plant activity, the vegetation rhythm may be expressed by the growth curve.

The course of development and the particular vegetation rhythm manifested by any plant is so intimately associated with climatic phenomena that it becomes necessary to bring Scharfetter's second term, the "climatic rhythm," defined as the annual course of meteorological phenomena, into the discussion at this point. The vegetation rhythm embodies the phenomena of the development of a plant during the course of the season and may be expressed readily in a graphic form by the growth curve; obviously, since climate is made up of the combined activities of numerous meteorological factors, the climatic rhythm cannot be so easily expressed by any single graphic expression.

External Factors in Relation to Periodicity. That all organisms pass through a definite cycle in their course of development has been pointed out. The exact course of this cycle is determined by both internal and external factors. In some instances, or in relation to certain phases, the external factors seem to have a greater influence in shaping the course of development than in others. Thus, Hildebrandt (18) and also Costantin (6) show that the length of life of a plant, that is, its behavior as an annual, winter annual, biennial, or perennial, is determined to a high degree by the external factors under which development proceeds. Muenscher (35) also points out that the behavior of weeds relative to their duration of life is not constant but "may be determined to a large extent by climatic factors. Many weeds that are annuals or biennials in very severe climates may act as biennials or perennials in milder climates or in seasons with mild winters." Red clover is generally regarded as biennial; however, in sections with mild climates, as in the Pacific Northwest, in the absence of plant diseases or insect pests, stands will survive for three to four years. The cotton plant behaves, or in reality is forced to behave under field conditions, as an annual; however, plants protected from low temperatures will survive for many years.

De Vries (10) reports an interesting case where deviations from the normal course of development were induced by nutritional changes.

Ordinarily, the normal course of development observed in nature or in cultivated plants, as stated by Klebs (22), is not determined from start to finish by the inherent constitution of the species. Klebs considers the constellation of external factors with which the plant comes in contact as constituting the primary force determining the course of development. Consequently, under altered external conditions an enforced deviation from the previously followed course may become evident. Exposure to low temperatures is not essential to the normal development of winter wheat. The rhythm in development ordinarily observed in its growth is an enforced rhythm. Low temperatures and low intensities of light constitute the limiting factors in autumn and during the winter months.

No doubt there is a distinct difference in the genetic constitution of true winter and spring wheats. This can be proved readily by hybridization and a study of the segregates resulting from such hybrids. When the differences in these two types of wheat are considered from the vegetative standpoint, it is evident that spring wheat varieties will not tiller as much or remain in the tillering stage as long as winter wheats. According to Körnicke (26), both spring and winter wheats undergo pauses in their respective courses of development. This pause is short in the case of the former and long in the case of the latter. In either instance the length of time that the plant will remain in the true vegetative phase can be influenced by environmental factors, especially by temperature, moisture, and light relationships. Klages (20) has shown that the differences in the vegetative behaviors of winter and spring wheats may be accentuated by variations in the amount of light provided to these plants.[1]

The time interval that winter wheats will remain in the vegetative stage can be reduced materially by vernalization. This process is also referred to under the terms of "iarovization" or "yarovization." As indicated by McKee (32), "vernalization is practically a seed treatment that influences the plant in its later stages of development." In the process of vernalization the seed is brought to visible germination and is then transferred and held at relatively low temperatures (3 to 5°C), with the moisture content maintained for from 35 to 45 days.

In view of the fact that the cycles of development in plants can

[1] See page 280, Chapter XVIII.

be modified by external conditions, their periodic behavior cannot be considered as resulting from internal factors only. In the case of winter wheat, dormancy is determined by external factors; it cannot be regarded, as Küster regards it [cited by Klebs (25)], as autogenous. One would hesitate to agree with Clements (4) that "changes or conditions connected with the resting period become fixed habits owing to their constant recurrence." Schimper (40) in his account of periodic phenomena of tropical vegetations states that "internal factors are mainly or solely responsible for the alteration of rest and activity in a nearly uniform climate." Klebs (24), however, not only doubts the accuracy of Schimper's statement as to the necessity of a period of dormancy in tropical plants, but also presents evidence to show that such periods of quiescence, when they do occur, are not produced by internal or hereditary factors but result from external conditions, either climatic or edaphic in nature. Under conditions of proper nutrition, tropical plants were grown in the greenhouse for a number of years without the intervention of a period of dormancy.

Klebs (23) comes to the conclusion that in the last analysis all variations from the commonly observed course of development are produced through changes in the environment which allow the inner potentialities of the organism to come to expression. Darwin (8) even earlier stated that "if it were possible to expose all the individuals of a species during many generations to absolutely uniform conditions of life there would be no variations." In order to determine the limits of variability, it is necessary to expose a plant to a great diversity of external conditions.

It must not be overlooked that in reality the external factors with which the plant comes in contact modify certain internal conditions within the plant so that the resulting behavior is due not directly but only indirectly to the reaction with the factors of the environment. It is not to be understood that external factors, as such, induce changes in the hereditary makeup or the genetic constitution of the plant. Reference is made here to certain definite chemical changes within the plant induced by variations in the factors of environment. Thus, the time of flowering, as pointed out by Möbius (33), is influenced markedly by external conditions, especially by light and moisture relationships. Fischer (12) and Loew (30) point out the importance of an abundant production of

carbohydrate materials to flowering. Kraus and Kraybill (27) are more specific in showing that the behavior of a plant with regard to vegetative growth and reproduction depends on the relative proportion of carbohydrates to nitrogenous materials within the plant. Such proportions, of course, are influenced greatly by external growing conditions. The more recent works of Garner and Allard (15) and (16) on photoperiodism in its relation to plant responses show definitely that plant reactions may be influenced greatly by exposure to varying lengths of days. More will be said about these interesting responses in the discussion of light relationships. It is not far afield to state then that in relation to factors determining their courses of development there is much the same condition in plants as Loeb (29) has indicated in his tropism theory of animal conduct. Thus, Loeb states and presents evidence to the effect that "motions caused by light or other agencies appear to the layman as expressions of will and purpose on the part of the animal, whereas in reality, the animal is forced to go where carried by its legs, for the conduct of animals consists of forced movements."

REFERENCES

1. Babcock, E. B., and R. E. Clausen, *Genetics in Relation to Agriculture.* McGraw-Hill, New York, 1918.
2. Baur, E., *Einführung in die experimentelle Vererbungslehre.* Gebrüder Borntraeger, Berlin, 1911.
3. Brody, S., "Growth and development with special reference to domestic animals: III. Growth rates, their evaluation and significance," *Mo. Res. Bull.* 97 (1927).
4. Clements, F. E., *Plant Physiology and Ecology.* Holt, New York, 1907.
5. Conklin, E. G., *Heredity and Environment.* Princeton Univ. Press, Princeton, 1916.
6. Costantin, J., *Les Végetaux et les Milieux Cosmiques.* Paris, 1898.
7. Coulter, M. C., *Outlines of Genetics.* University of Chicago Press, Chicago, 1923.
8. Darwin, C., *The Origin of Species.* Appleton, New York, 1881.
9. De Vries, H., *Intracellular Pangenesis.* Open Court Pub. Co., Chicago, 1910 (first published in 1889).
10. ———, *The Mutation Theory,* Vol. 1. Open Court Pub. Co., Chicago, 1909 (first published in 1903).
11. East, E. M., "The Mendelian notation as a description of physiological facts," *Am. Nat.,* 46:633–655 (1912).

12. Fischer, H., "Über die Blütenbildung in ihrer Abhängigkeit vom Licht und über blütenbildenden Substanzen," *Flora*, 94:478–490 (1905).
13. Frost, H. B., "The different meanings of the term 'factor' as affecting clearness in genetic discussion," *Am. Nat.*, 51:244–250 (1917).
14. Gaines, W. L., and W. B. Nevens, "Growth-equation constants in crop studies," *Jour. Agr. Res.*, 31:973–985 (1925).
15. Garner, W. W., and H. A. Allard, "Flowering and fruiting of plants as controlled by length of day," *U. S. Dept. Agr. Yearbook* 1920:377–400.
16. ———, "Further studies in photoperiodism, the response of the plant to relative length of day and night," *Jour. Agr. Res.*, 23:871–921 (1923).
17. Haecker, V., *Entwicklungsgeschichtliche Eigenschaftsanalyse.* Jena, 1918.
18. Hildebrandt, F., "Die Lebensdauer und Vegetationsweise der Pflanzen, ihre Uhrsachen und ihre Entwicklung," *Englers. Bot. Jahrb.* 2:51–134 (1882).
19. Johannsen, W., *Elemente der Exakten Erblichkeitslehre.* Jena, 1913.
20. Klages, K. H. W., "Metrical attributes and the physiology of hardy varieties of winter wheat," *Jour. Amer. Soc. Agron.*, 18:529–566 (1926).
21. ———, "The value and application of growth curves to field plat experiments," *Jour. Amer. Soc. Agron.*, 25:453–464 (1933).
22. Klebs, G., "Problem der Entwicklung," *Biol. Centrlbl.* 24:257–267, 289–305 (1904).
23. ———, "Über Variationen der Blüten," *Jahrb. f. wiss. Bot.* 42:155–320 (1905).
24. ———, "Über die periodischen Erscheinungen tropischer Pflanzen," *Biol. Centrlbl.* 32:257–285 (1912).
25. ———, *Über das Verhältnis der Aussenwelt zur Entwicklung der Pflanzen.* Sitzungsbr. der Heidelberger Akad. D. Wissenschaften. Jahrgang 1913. 5 Abhandlung. 1913.
26. Körnicke, F., *Arten und Varietäten des Getreides.* Berlin, 1885.
27. Kraus, E. J., and H. R. Kraybill, "Vegetation and reproduction with special reference to the tomato," *Ore. Agr. Exp. Sta. Bull.* 149, 1918.
28. Lefevre, G., "Heredity and environment," *Amer. Orthodontist* 1:1–23 (1906).
29. Loeb, J., *Forced Movements, Tropism, and Animal Conduct.* Lippincott, Philadelphia, 1918.
30. Loew, O., "Zur Theorie der blütenbildenden Stoffe," *Flora* 94:124–128 (1905).
31. McGee, W. J., "The relation of institutions to environment," *Ann. Rpt. Smithsonian Inst.*, 1895. V. 50, Pt. 1:701.

32. McKee, R., "Vernalization experiments with forage crops," *U. S. Dept. Agr. Cir.* 377, 1935.
33. Möbius, M., "Welche Umstände fördern und welche hemmen das Blühen der Pflanzen," *Biol. Centrlbl.* 12:609–624, 673–687 (1892).
34. Morgan, T. H., *Evolution and Adaptation.* Macmillan, New York, 1908.
35. Muenscher, W. C., *Weeds.* Macmillan, New York, 1935.
36. Priestley, J. H., and W. H. Pearsall, "An interpretation of some growth curves," *Ann. Bot.*, 36:238–249 (1922).
37. Rippel, A., "Über die Wachstumskurve der Pflanzen," *Landn. Vers. Stat.*, 97:357–380 (1920).
38. Robertson, B. R., "On the normal rate of growth of an individual and its biochemical significance," *Arch. Entw. Mech.*, 25:581–614 (1908).
39. Scharfetter, R., "Phenology and agriculture," *Int. Rev. Sci. & Pract. of Agr.*, 1:561–572 (1923).
40. Schimper, A. F. W., *Plant Geography upon a Physiological Basis.* Clarendon Press, Oxford, 1903.
41. Schmidt, O., "Über den Entwicklungsverlauf beim Getreide," *Landw. Jahrb.* 45:267–324 (1913).
42. Sharp, L. W., *Introduction to Cytology.* McGraw-Hill, New York, 1921.
43. Werneck, H. L., "Phenology in its application to agriculture," *Int. Rev. Sci. & Pract. of Agr.*, 2:13–21 (1924).

Chapter VIII

PHYSIOLOGICAL LIMITS

The Cardinal Points of Vital Activity. The general reactions of an organism to the factors of the environment were discussed in some detail in the previous chapter. Special reactions will now be dealt with. All plant activities operate within certain more or less well-defined limits. A seed cannot germinate and a young seedling is incapable of development unless the environment supplies certain definite requirements as to temperature, moisture, oxygen, carbon dioxide, mineral nutrients, etc. The requirements of life must be present at least in the minimum quantity, concentration, or form before the manifestations of life and growth can be either initiated

TABLE 3. THE CARDINAL POINTS FOR GERMINATION OF SOME IMPORTANT CROPS, TAKEN FROM HABERLANDT

Crop	*Cardinal Points, in Degrees Centigrade*			*Number of Days Required for Germination (the breaking through of the roots) at the Indicated Temperatures, in Degrees Centigrade.*			
	Minimum	Maximum	Optimum	*4.38*	*10.25*	*15.75*	*19.00*
Wheat	3–4.5	30–32	25	6	3.0	2.0	1.75
Rye	1–2	30	25	4	2.5	1.0	1.0
Barley	3–4.5	28–30	20	6	3.0	2.0	1.75
Oats	4–5	30	25	7	3.75	2.75	2.0
Corn	8–10	40–44	32–35	—	11.25	3.25	3.0
Sorghums	8–10	40	32–35	—	11.5	4.75	4.0
Rice	10–12	36–38	30–32	—	—	—	—
Timothy	3–4	30	26	—	6.5	3.25	3.0
Flax	2–3	30	25	8	4.5	2.0	2.0
Tobacco	13–14	35	28	—	—	9.0	6.25
Hemp	1–2	45	35	3	2.0	1.0	1.0
Sugar Beet	4–5	28–30	25	22	9.0	3.75	3.75
Red Clover	1	37	30	7.5	3.0	1.75	1.0
Alfalfa	1	37	30	6	3.75	2.75	2.0
Peas	1–2	35	30	5	3.0	1.75	1.75
Lentils	4–5	36	30	6	4.0	2.0	1.75
Vetch	1–2	35	30	6	5.0	2.0	2.0

or sustained; these manifestations proceed at the highest rate of activity at the optimum and again come sooner or later to a close at the maximum point. These three points of relative rate of activity are referred to as the cardinal points.

The cardinal points are not so definite as was formerly supposed; they are subject to a considerable range, depending on the environmental factors under which the plant develops and the condition and age of the plant. Pfeffer (11) early recognized that "the cardinal points can never be determined with more than the approximate accuracy, since their position is involved by the external conditions, by the duration of exposure, by the age of the plant, and by its previous treatment."

Haberlandt, cited by Grafe (4), gives the cardinal temperature points for the germination of seeds of a large number of plants. Table 3 gives these cardinal points as represented by him for some of the more important crop plants.

The Time Factor in Relation to the Location of Cardinal Points. The activity of separate environmental factors such as temperature above the maximum will sooner or later result in a cessation of all manifestations of life. For short periods supramaximal temperatures may not have lasting detrimental effects; if the plant, however, remains for any length of time exposed to such supramaximal factors, death is certain to result. The effect of length of exposure to given temperatures on the location of the optimum is shown in Fig. 6, taken from the work of Talma cited by Benecke and Jost (1). The rate of activity of *Lepidium sativum* exposed to the temperatures indicated for intervals of 3½, 7, and 14 hours was measured by the increases in the length of the roots. A short exposure, 3½ hours, showed an optimum temperature at 30°C. With the doubling of the time interval the optimum was found at 29°C, and when the period of exposure was lengthened to 14 hours, the highest rate of activity was in evidence at 27.2°C. The increase in temperature, especially with the longer periods of exposure, exerts influences depressing to growth. These growth-depressing factors become more and more active with the approach of the optimum point and beyond it account for the rapid downward trend of the growth curves. This is only one example of the influence of the time factor on the exact position of the optimum. Numerous other illustrations could be given.

The Stage of Development in Relation to Cardinal Points. The determination of cardinal points is of practical value only when correlated with a particular developmental stage in the life rhythm of the plant. It is obvious from Table 3 that most of the heat-loving plants such as corn, the sorghums, rice, and tobacco exhibit rather high minima. It does not follow, however, that a

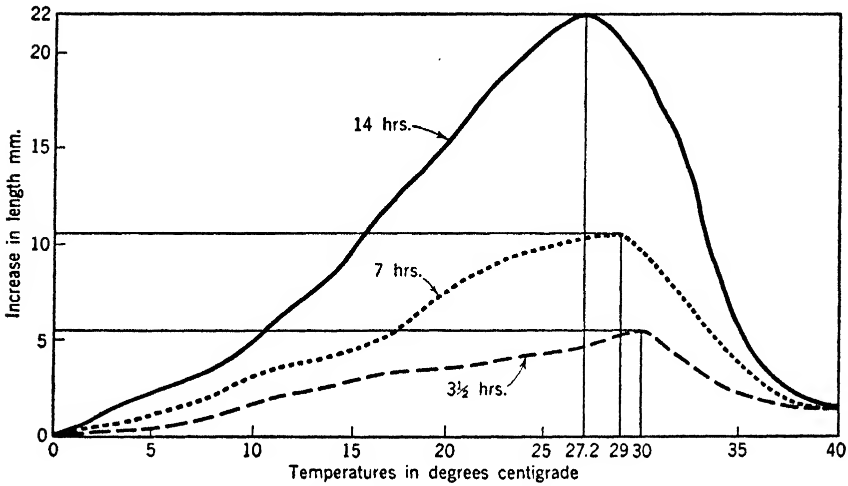


FIG. 6. Relationship of the time of exposure in hours to the rate of growth, elongation in the length of the roots of *Lepidium sativum*, and the location of the optima for the various time intervals. (After Talma.)

high temperature requirement during an early stage of development such as germination is necessarily correlated with a high temperature requirement during subsequent periods of development. It will be noted that while the minimum temperature for the germination of hemp is low, this plant can nevertheless be classified as a heat-loving crop during its later stages of growth. Some indications of this fact are given by the high values of the maximum and optimum temperatures for its germination.

Schimper's Optima. Schimper (12) coined three terms which can be used to good advantage for purposes of illustrating the reactions of plants to increasing intensities of a particular factor of the environment. These terms are the "absolute," "harmonic," and "ecological optima." These optima may be taken in a broader sense than the previously considered cardinal points, and their meanings can be extended as was done by Werneck-Willingrain

(16 and 17) and Klages (8 and 9) to apply to problems encountered in the general distribution of crop plants.

The *absolute optimum* corresponds to the highest degree of activity of any one function of a plant such as transpiration or respiration. With increasing temperatures the plant, up to a certain point, transpires at given intervals ever-increasing amounts of water. Beyond this particular point, because of interference or the breakdown of certain of the intricate portions of the organism, the rate of activity decreases sharply. The optimum point of activity may, therefore, be defined as that point where limiting factors or checks come into activity.

The *harmonic optimum* corresponds to the most favorable intensity of any one function in relation to the other functions of the plant. Transpiration increases up to a certain point with increasing temperatures. While transpiration is a necessary function of the plant, an excessive activity of this particular, or of any other, function would soon lead to the destruction of the plant. The plant reaches its highest activity at that particular point where the rates of activities of the various functions are in harmony with each other or, in other words, at that point where they are properly coordinated.

The *theoretical ecological optimum* consists of the summation of the various harmonic optima. It is difficult to give the exact location of the summation of the various harmonic optima or the exact location of the ecological optimum. In speaking of the summation of the various harmonic optima, it is necessary not only to locate an average point but also to consider the relative importance of each of the various functions of the plant in their relation to the growth and behavior of the entire organism.

The Ecological Optimum and Crop Distribution. Schimper's theoretical ecological optimum can, according to Lundegårdh (10), hardly be realized under a constant set of external conditions but corresponds rather to a definite type of climate in which the various phases of development proceed under changing climatic conditions with the advance of the season. Klages (8 and 9), working with the yields of cereal and corn crops in the states of the Mississippi Valley and in South Dakota, made use of Schimper's terminology. The fact that a crop or a group of crops is well adapted to a given region is shown by uniformly high average yields for such crops with a minimum of variability in seasonal yields. The theoretical

ecological optimum for a crop is approached in those particular geographical locations where it exhibits high average yields with a relatively low seasonal variability in such yields, or, in other words, in those sections where the yields are high and the hazards of production are low, ensuring a high degree of stability to production enterprises.

Werneck-Willingrain, in his attempts to place the tasks of the crop breeder upon a physiological basis, also makes good use of Schimper's theoretical ecological optimum. A plant breeder in his efforts to breed crops adapted to a particular environmental complex must, if he expects to produce improved varieties with a minimum of effort and expense, first of all have a good understanding of the external factors with which his new creations will react. It must be recognized that cropping areas, and in them varietal areas, extend from minimal to optimal sections. In the former, environmental conditions barely satisfy the life requirements in an average season, or as Werneck-Willingrain (16) puts it, only the minimal life requirements (Minimum der Lebensbedingungen) are present. Under such conditions marked seasonal fluctuations in yields can be expected. In the optimal sections average conditions approach the optimum. These are the locations where uniformly high yields and stability of production are to be found. Figure 7 taken from Werneck-Willingrain's (17) paper, shows graphically a natural distribution of a plant species over regions with variable environmental conditions. The species, and this may apply in equal degree to a crop or more specifically to a variety of a given crop, is distributed from a minimal to an optimal area which may or may not be contiguous. Climatic and edaphic factors come definitely into play in these areas and in the transitional zones separating them.

Huntington *et al.* (7) in their studies of interrelations of climatic factors to yields make use of isopleths (lines connecting regions with equal crop yields) and climographs. Such a method brings out some interesting relationships between yields and climatic factors. It has general application, however, only to sections where the crop under consideration is general or is being grown on an extensive scale and not to those regions where the crop is grown only on highly selective or highly favored areas, as corn in the New England states. High yields of corn in the New England and North

Atlantic states are due to the special attention given the corn crop there rather than to favorable climatic conditions. When Huntington's analysis of yields in relation to climatic conditions is employed in such regions, misleading deductions can easily be made.

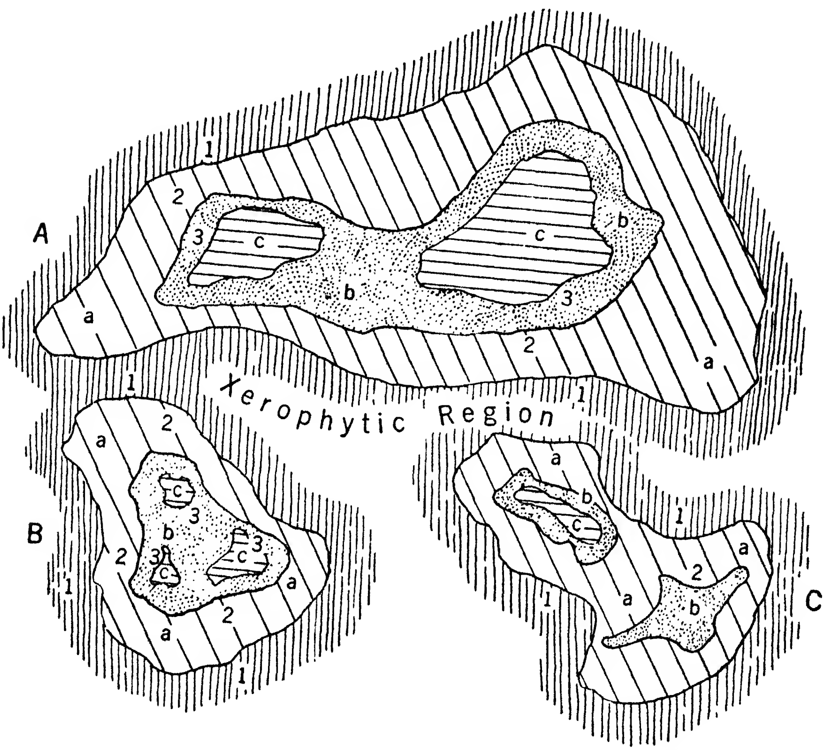


FIG. 7. Model of the natural distribution of a species. (After Werneck-Willingrain.) *A*, transition lines: 1, minimal threshold; 2, threshold of the moderate area; 3, threshold of the most favored area, *a*, minimal region; *b*, moderate region; *c*, optimal region. *B* and *C*, separated distribution areas of the same species. *B*, *c*, most favored belt on account of high humus content of soil or abundance of moisture. *C*, *b*, remains in moderate region due to unfavorable soil relationships; *c*, most favored belt due to optimal moisture relationships.

Limiting Factors. On the question of limiting factors, a very considerable literature has developed, and numerous theories have been advanced, since the appearance of Blackman's (2) initial paper. Blackman set forth the axiom that "when a process is conditioned as to its rapidity by a number of separate factors, the rate of the process is limited by the pace of the slowest factor." Blackman's axiom of limiting factors is in reality an elaboration of

Liebig's law of the minimum which in its essence, as may be noted from its wording, is very similar. "The yield of any crop always depends on that nutrient constituent which is present in the minimum amount." Both statements are firm and exacting, giving little play for the effects of other factors influencing activity.

Hooker (6), in a study of the law of the minimum, comes to the conclusion that "a biological phenomenon is dependent not on a single variable, but on a complex or constellation of factors." From this he continues that "individual processes obey the law of the minimum; but the grand total is governed by what may be termed a principle of integration."

Harder (5), in a critical study concerning Blackman's limiting factors in carbon dioxide assimilation, found no evidence of the sharp angle at the point where the limiting factor is supposedly to enter. Instead his curves approached the horizontal position gradually.

The above contentions are borne out by numerous other investigations. Crocker (3) concludes that the law of limiting factors does not apply to plant activities so generally or with anything like the degree of rigidity assumed by some investigators. He suggests that the question should be not so much what external factor is the limiting one, but rather what internal condition or inhibitor must this factor act upon in order to indicate the reaction that is under consideration.

More will be said regarding optima and limiting factors in relation to crop adaptation in Chapter X in connection with a discussion on critical periods in crop production. At this time a consideration of the general aspects of the topic is sufficient.

Practical Applications of the Theory of Optima and Limiting Factors. In a consideration of the great crop producing provinces of the world, it is possible to take each particular area and classify for each one the factors favorable to the production of a particular crop or group of crops. Finally, as the outer fringe of cultivation is approached, it is also possible to classify various factors that are adverse to crop production. This task is best accomplished in connection with the discussion of ranges of adaptation of each individual crop. It is well at this time, however, to give a broad outline of limits to crop production. As stated by Spafford (13),

"the boundaries of the four great agricultural regions in the Northern Hemisphere are determined by low temperature, low rainfall and coast line. In southern Canada, Norway, Sweden and Finland and in northern Russia, Manchuria and Japan agriculture is limited by low temperature. The principal boundaries determined by low rainfall in North America are found (*a*) in the states of the Great Plains and (*b*) in the states of the Pacific Coast region. In Eurasia the principal agricultural boundaries determined by low rainfall are found (*a*) in southeastern Russia and (*b*) in western China proper and Manchuria."

FIG. 8. The principal boundaries of the agricultural regions of North America. The small circles mark temperature limits and the dashes rainfall limits. (After Spafford.)

These agricultural boundaries for the continents of North America, Europe, and Asia are presented in Figs. 8, 9, and 10. Similar limitations for crop production can be pointed out for Africa, where production in the north and also in the south is definitely limited by areas of low rainfall. A very good discussion of factors limiting agricultural production in southern Africa is given by C. C. Taylor (14). In South America agricultural production is limited by low rainfall in the interior and in the western areas, by low temperatures in the extreme south, and by poor soil and climatic conditions in the equatorial regions. These same limiting factors are also very

much in evidence in Australia. Griffith Taylor (15) points out that 94 per cent of the total rural population of Australia is found on the margins of that continent and only 6 per cent on the "sparse-lands." The strictly agricultural lands of the continent, excluding the pastoral regions, are even more limited than the above figures on distribution of population indicate.

FIG. 9. The principal boundaries of the agricultural regions of Europe. The small circles mark temperature limits and the dashes rainfall limits. (After Spafford.)

Producers in any given area can, insofar as environmental factors permit, arrange their cropping practices so that conditions in general may approach the optimum. It is necessary, as has previously been pointed out, to recognize the physiological limitations of any given locus in order to arrive at an economic utilization of the land resources of any region. Crop yields may be increased by various methods such as proper cultural practices, sequences of cropping, addition of elements present in minimal quantities, addition of water, utilization of adapted varieties, and control of diseases, insect pests, etc. All of these various means of increasing yields can, however, be expected to produce economic gains only insofar as environmental complexes permit. Willcox (18) attempts to cal-

culate the "limits of crop yields" with the aid of the much-discussed and debated Mitscherlich formula. That the yield curve of any plant under the action of any specific growth factor is definitely asymptotic has long been known. The exact shape of the curve produced depends, however, not only on the factor added at given increasing rates, but rather on the sum total of all environmental

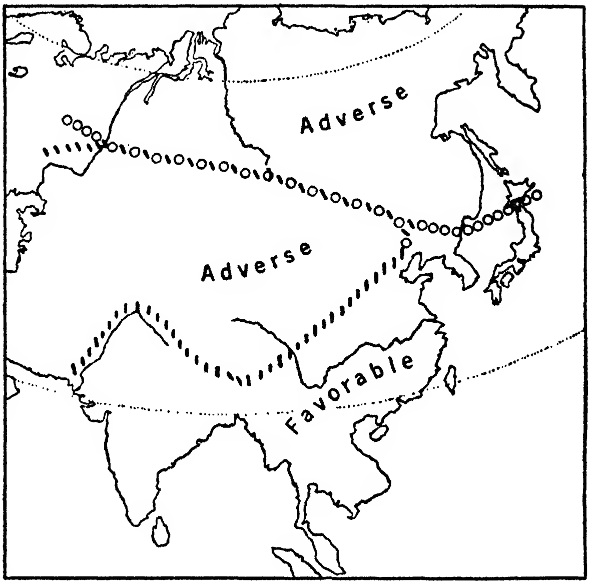


FIG. 10. The principal boundaries of the agricultural regions of Asia. The small circles mark temperature limits and the dashes rainfall limits. (After Spafford.)

factors with which the plant reacts. In the light of this, the theoretical determinations of Willcox's upper "limits of crop yields" become of very questionable value. The all-important problem of agricultural production is not one of obtaining simply the highest possible yields but rather of so shaping the production program that economic production may result and a permanent agricultural system be established and maintained.

REFERENCES

1. Benecke, W., and L. Jost, *Pflanzenphysiologie*, Vol. 2. Gustav Fischer, Jena, 1923.
2. Blackman, F. F., "Optima and limiting factors," *Ann. Bot.*, 19:281-295 (1905).

3. Crocker, W., "Law of the minimum — a review of Hooker's work," *Bot. Gaz.*, 65:287–288 (1918).
4. Grafe, V., *Ernährungsphysiologisches Praktikum der höheren Pflanzen.* Paul Parey, Berlin, 1914.
5. Harder, R., "Kritische Versuche zu Blackman's Theorie der 'begrenzenden Faktoren' bei der Kohlensäure Assimilation," *Jahrb. f. wiss. Bot.*, 60:531–571 (1921).
6. Hooker, H. D., "Liebig's law of the minimum in relation to general biological problems," *Science*, 46:197–204 (1917).
7. Huntington, E., F. E. Williams, and S. Van Valkenburg, *Economic and Social Geography.* Wiley, New York, 1933.
8. Klages, K. H. W., "Geographical distribution of variability in the yields of field crops in the states of the Mississippi Valley," *Ecology*, 11: 293–306 (1930).
9. ———, "Geographical distribution of variability in the yields of cereal crops in South Dakota," *Ecology*, 12:334–345 (1931).
10. Lundegårdh, Henrik, *Klima und Boden in ihrer Wirkung auf das Pflanzenleben.* Gustav Fischer, Jena, 1925.
11. Pfeffer, W., *The Physiology of Plants*, trans. and rev. by A. J. Ewart, Vol. 2. Clarendon Press, Oxford, 1903.
12. Schimper, A. F. W., *Plant Geography upon a Physiological Basis.* Clarendon Press, Oxford, 1903.
13. Spafford, R. R., "Farm types in Nebraska, as determined by climatic, soil and economic factors," *Nebr. Res. Bull.* 15, 1919.
14. Taylor, C. C., "Agriculture in southern Africa," *U. S. Dept. Agr. Tech. Bull.* 466, 1935.
15. Taylor, Griffith, "The frontiers of settlement in Australia," *Geog. Rev.*, 16:1–25 (1926).
16. Werneck-Willingrain, G. L., "Die Pflanzenzüchtung auf pflanzengeographischer Grundlage," *Pflanzenbau. Jahrg.*, 1924:145–150.
17. ———, "Der Getreidebau auf pflanzengeographischer Grundlage," *Pflanzenbau., Jahrg.*, 1924–25:393–404, 419–425.
18. Willcox, O. W., "What is agrobiology?" *Econ. Forum*, Winter 1936 issue: 302–310.

Chapter IX

CROP YIELDS AND VARIABILITY IN RELATION TO THE ECOLOGICAL OPTIMUM

Broad Conception of the Ecological Optimum. The ecological optimum, as defined by Schimper, is generally regarded as a purely hypothetical entity. It will now be shown that a broad conception of this term can be of considerable value in the study of ecological crop geography. The materials used in this chapter are taken largely from two papers by the author, Klages (4 and 5).

The potential crop producing ability of a given area is dependent primarily upon the existing climatic and soil conditions under which the crops in question must be grown. Since climatic factors exert mainly a regional influence on plant life, the differences in the behavior of a crop or a group of crops over extensive areas, as in a given state or a group of states, may be considered due, primarily, to differences in climatic rather than soil conditions.

In regions of the ecological optimum of a crop, it is to be expected that the yields should be uniformly high, while the variations in such yields from season to season should be fairly low. A low variation in the yields of a crop over a period of years serves as a measure of stability of production insofar as the returns from a given acreage can be ascertained in advance with a reasonable degree of certainty. An excessively high degree of variability in the yields of one or more crops in a given area indicates that certain hazards are encountered in the production of that particular crop or series of crops. As stated by Clements (1), "every plant is a measure of the conditions under which it grows. To this extent it is an index of soil and climate, and consequently an indicator of the behavior of other plants and animals in the same spot."

With the above factors in mind, Klages (4) tabulated the yields of grain crops in the states of the Mississippi Valley, and calculated the degree of variability in the seasonal yields of these respective crops. The average yields of these states offered very suitable data

as the eastern states of this extensive crop area have typical woodland climates, while the climates of the states of the Great Plains area, especially in the central and western portions of these states, are decidedly of a grassland type.

All yields and tabulations, with the exception of those of the state of Oklahoma, are based on results reported for a period of 37 years, 1891–1927, inclusive. The data for Oklahoma were available only for a 27-year period, 1901–1927, inclusive. Since the data pertaining to the discussion of the facts presented in this chapter can be given readily in graphical form, tabulations of these data are not included here. Students interested in greater detail than space permits here are referred to the original papers (Klages, 4 and 5).

In the graphic presentation, the same linear scale was used for both the yield and variability data. This method may be criticized from a strictly mathematical standpoint in that the variability expressed on a percentage basis is in certain instances greater than the yield expressed in bushels. It is justifiable in this case as it presents the clearest possible graphical presentation of the facts. It also is to be recognized that the coefficient of variability is not beyond reproach in all instances as an expression of degree of variation; however, the type of data here analyzed may well be treated on the basis of percentage variability. Klages (5) made use of both the coefficient of variability and Weinberg's formula and arrived at the same conclusion.

Yields and Variability of Yields of Corn. Corn is an important crop in all the states of the Mississippi Valley. Figure 11 shows graphically the average yields and variability of the yields of corn in the separate states.

It will be seen that the yields decrease in all instances in going from east to west, except in the most southern tier of states. The average yields of the Great Plains states are significantly lower than those of the states to the east of this area. These differences are brought out not only by the respective means but also by the lower values of the modal classes. This condition is to be expected in view of the lower amounts of precipitation in the Great Plains area. As stated by Waller (9), "to say that there is more abundant moisture in the prairies than in the plains is only another way of saying that there is more abundant vegetation." Another factor to be considered in the Great Plains area is the higher rate of evaporation.

The tendency for yields to decrease either to the north or to the south of the heart of the Corn Belt is apparent. This holds true along the line from Ohio through to Nebraska.

The coefficients of variability of corn yields increase decidedly from the eastern to the western states, as do also the ranges in yield

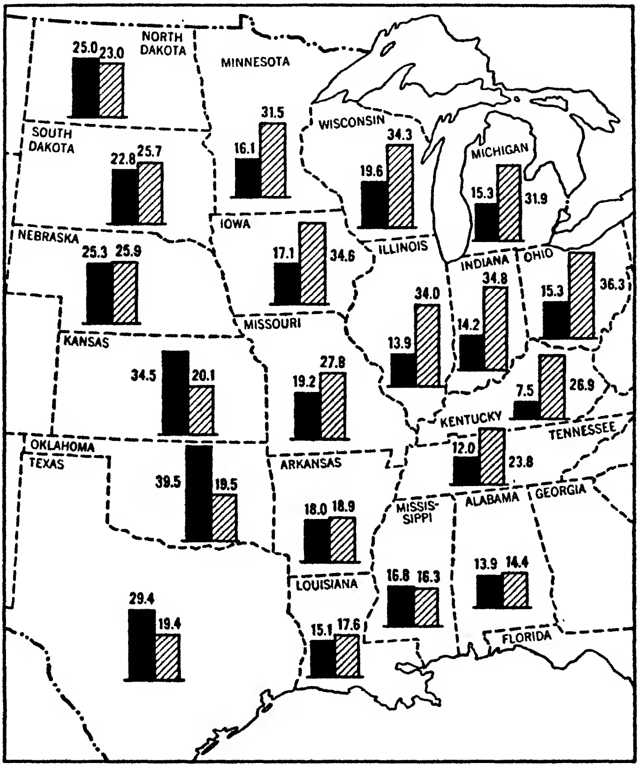


Fig. 11. Average yields (cross-hatched columns) and coefficients of variability for the yields (solid columns) of corn in the states of the Mississippi Valley.

from year to year, but to a lesser degree. The lowest yields reported for each tier of states from north to south are invariably to be found in the states of the Great Plains area.

It is apparent that the region of the ecological optimum for corn production is to a great extent determined by the specific interaction of climatic factors. Weaver (12) points out the specific effects of climatic factors on the development of the corn plant in the drier sections of the Great Plains area, while Miller (6) shows from a physiological standpoint why the production of grain sorghums is

less hazardous in this region than corn production. Since soil factors vary within the units selected, no attempt is made to evaluate them in this chapter.

Yields and Variability in the Yields of Oats. The average yields and degrees of variability for oats are shown graphically in Fig. 12.

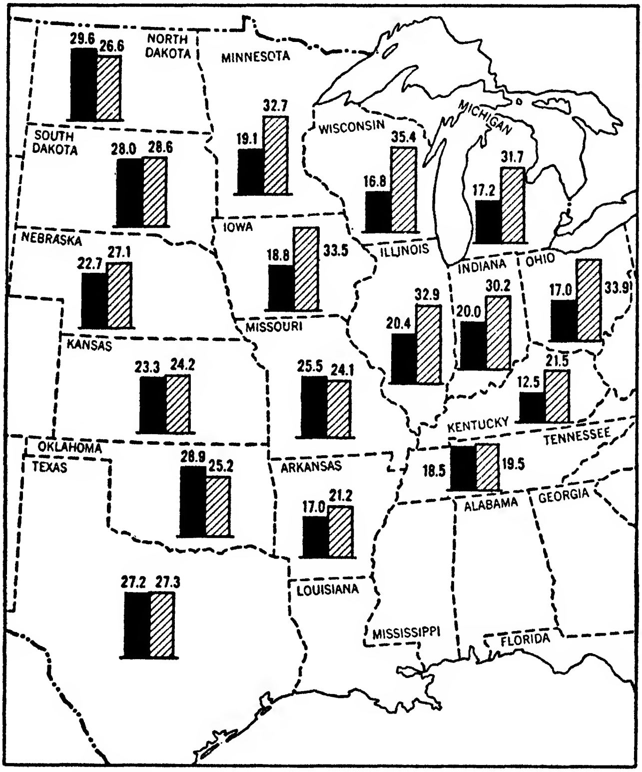


FIG. 12. Average yields (cross-hatched columns) and coefficients of variability for the yields (solid columns) of oats in the states of the upper and central Mississippi Valley.

As in the case of corn, a material reduction of the yields in the western states is in evidence. The lowest yields for the respective groups of states are also to be found here.

The variability of yields increases from east to west as in the case of corn; the differences are not so pronounced, however. The detrimental effects of high summer temperatures occasionally encountered in the Corn Belt states are brought out by the relatively

high coefficients for such states as Indiana, Illinois, and Missouri. The low coefficients of variability of the yields of such states as Kentucky, Tennessee, and Arkansas may be accounted for by the fact that these states produce but few oats.

The highest yields, especially as shown by the modal classes, are encountered in Ohio, Michigan, Wisconsin, and Minnesota. The Corn Belt states show fairly high average yields but lower modal classes. Of the southern states, Oklahoma and Texas show high yields. These states show, however, like other states of the Great Plains area, high degrees of variability in yields.

The data presented show that the region with the most favorable climatic conditions, the ecological optimum, for oat production is to be found somewhat to the north of the heart of the Corn Belt, where moderate summer temperatures prevail.

Yields and Variability in the Yields of Wheat. The yield data available on wheat allowed for no distinctions between spring and winter wheat except insofar as states producing predominately one or the other of these wheats are represented. The yield and variability data for the crop are presented in Fig. 13.

The data presented indicate that different types of hazards are encountered in the various wheat producing areas of the Mississippi Valley. The spring wheat producing states, from Wisconsin to the Dakotas, show the same yield and variability relationships as shown by corn and oats, namely, lower yields and higher variability in the drier western states. The high degree of variability in the yields of the spring wheat producing states of the Great Plains area is accounted for by the rather high frequencies of droughts and occasional severe epidemics of stem rust. It should be noted also that spring wheat production is generally more hazardous than the production of winter wheat. Since winter wheat matures earlier than the spring-sown crop, it is in a better position to escape damage from drought and rust. The lower degree of variability in Nebraska as compared to South Dakota is due in part to the fact that the former state produces largely winter wheat and the latter produces mainly spring wheat. It is interesting to note the rather high degrees of variability for the eastern soft red winter wheat producing states. The coefficients for the western hard red winter wheat producing states are comparatively low, especially when compared with the uniformly high degrees of variability shown by

other crops in these states. Winterkilling constituted a hazard in all the winter wheat producing areas of this region. Both stem and leaf rusts are of greater consequence in the more humid eastern states than in the drier western areas. On the other hand, lack of moisture in autumn at the time of seeding, or later, as well as during

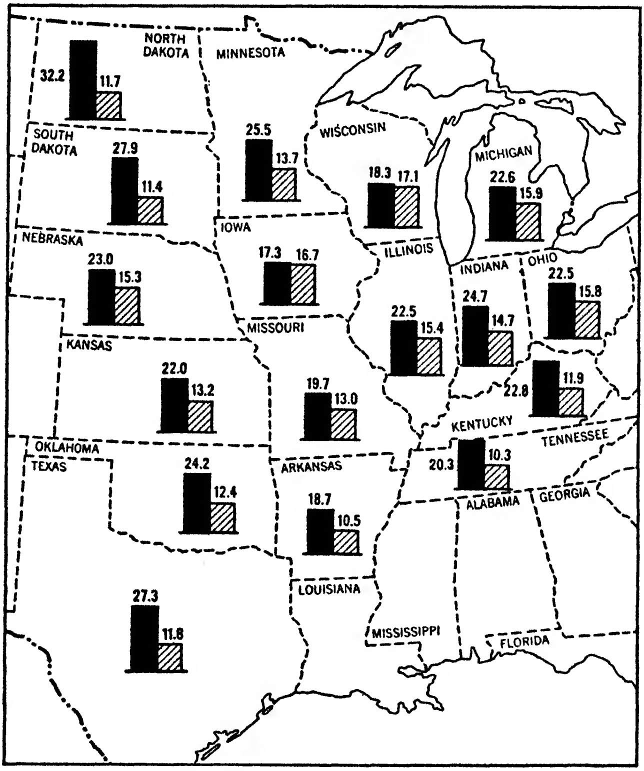


FIG. 13. Average yields (cross-hatched columns) and coefficients of variability for the yields (solid columns) of wheat in the states of the Mississippi Valley.

the growing season of the crop, constitutes a greater hazard in the western areas than in the eastern areas of this region.

Yields and Variability in the Yields of Barley. The yields of barley in the several states do not differ so greatly as those of other crops reported. Differences in the variability of yields, however, are very pronounced, as shown graphically in Fig. 14. The states of the Great Plains, especially Kansas and North Dakota, exhibit exceedingly high coefficients of variability.

It is rather significant that the degrees of variability for the yields

of barley are much lower than those of oats, except in the Great Plains; this is apparent from a comparison of Figs. 12 and 14. There may be several reasons for this. It may be that more attention is devoted to barley production, both from the standpoint of cultural practices and the selection of more favored locations, as

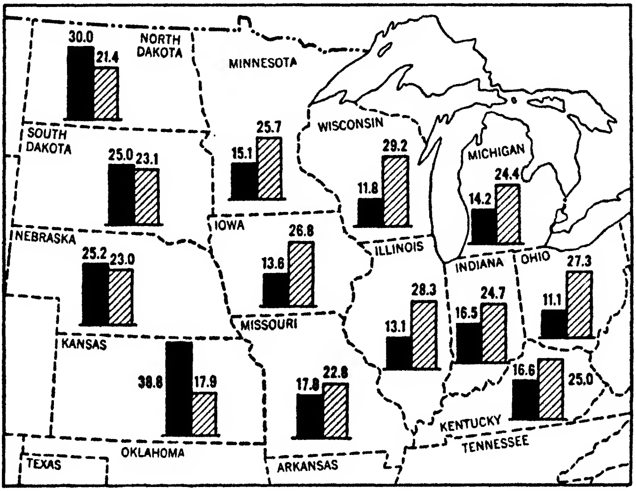


Fig. 14. Average yields (cross-hatched columns) and coefficients of variability for the yields (solid columns) of barley in the states of the upper Mississippi Valley.

on more fertile and better watered soils. Barley generally matures somewhat earlier than oats, especially in sections where medium- to late-maturing varieties of oats are commonly grown. This enables the barley crop to escape some of the high summer temperatures occasionally encountered in the states of the Mississippi Valley. On the other hand, as brought out by Hutcheson and Quantz (3) and by Walster (10), barley is more sensitive to high temperatures than oats. This may account for the slightly higher degrees of variability of the yields of barley as compared to those shown by oats in the states of the Great Plains, where summer temperatures are fairly high and where the production of early-maturing varieties of oats is the rule.

Yields and Variability in the Yields of Rye. The yields and degrees of variability for rye (Fig. 15) show much the same trend as those given for barley. The coefficients of variability are significantly higher for the western than for the eastern states.

It will be observed that the degrees of variability for the yields of rye are less than those of any other crop. The ability of rye to grow under more unfavorable conditions than other cereal may account for this fact.

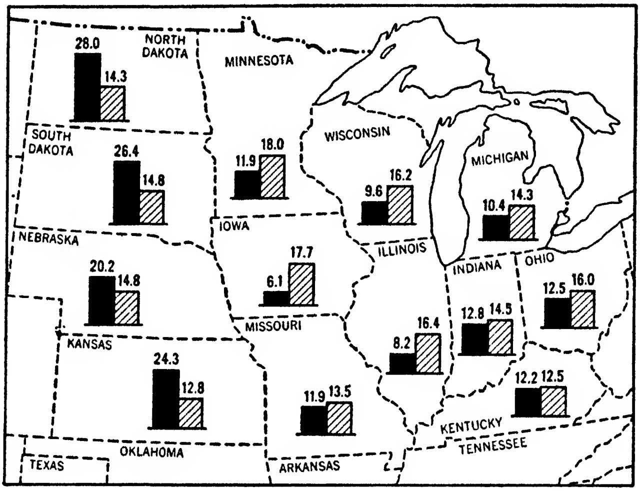


FIG. 15. Average yields (cross-hatched columns) and coefficients of variability for the yields (solid columns) of rye in the states of the upper Mississippi Valley.

The Ecological Optimum Region of a Crop Is Determined by the Factors of the Physiological and Social Environment. The foregoing discussion based on the analysis of yield data of the states of the Mississippi Valley serves to substantiate the theory previously stated, namely, that the region to which a crop is best adapted may often be located on the basis of uniformly high yields of the crop in question. Exceptions to this general statement were found in the case of states where the production of the crop under question was of relatively little importance. Another exception was the behavior of yields of wheat in the states producing hard red spring wheat. Yields in these states were fairly low while the degrees of variability were high. Still, the type of crop grown in this section can hardly be compared with that grown in the states to the east; its very nature is determined by the climatic conditions under which it is produced. Hard red spring wheats cannot be produced in the humid eastern area of the United States or Canada. The hard vitreous character of the kernels and the high nitrogen content of

this class of wheat are determined not only by the genetic factors of the varieties employed, but to a large degree by the type of climate and the soil conditions under which the crop is grown. The typically grassland climates prevailing in the northern Great Plains area are characterized by a relatively abundant supply of moisture during the early vegetative period but a rapidly decreasing availability of moisture during the early part of the summer. The decrease in moisture available to the plants corresponds well with the postheading period of spring wheat. This more or less progressive decrease in the availability of moisture tends to cut down the time interval from flowering to maturity. The climatic conditions and the types of soil produced under such climatic complexes account for the relatively low yields, yet at the same time they play an important part in determining the chemical and physical properties of the crop produced.

Variability in the Yields of Crops in the Eastern and Central Great Plains Area. The foregoing discussions on crop yields and variabilities of such yields in the states of the Mississippi Valley in their relation to the ecological optimum is subject to criticism from the standpoint of the size of the units used. Climatic conditions of as large an area as the confines of a state are far from uniform. This is true especially for the states of the Great Plains region, the eastern portions of which show a type of climate entirely different from that of the central and western parts. As may be observed from the maps of natural vegetations given by Shantz and Zon (8), and from the numerous root studies of native plants by Weaver (11), and by Weaver and Crist (13), entirely different types of vegetations, which reflect directly the prevailing climatic conditions, are encountered in the eastern and western portions of these states. Consequently, the yield data of such large units have all the shortcomings of average values.

The distribution of the main station and the various substations of the South Dakota Agricultural Experiment Station was found favorable for a more definite investigation on variability of crop yields (Klages, 5). The main station at Brookings is located in the east-central part of the state, only 18 miles from the Minnesota line. The Highmore substation is located in the central part, 150 miles west of Brookings, while the Eureka substation is found 100 miles north of Highmore, near the North Dakota state line.

Figures 16 and 17 give a graphic presentation for a 21-year period, 1909–1929, inclusive, of the yields and seasonal variabilities

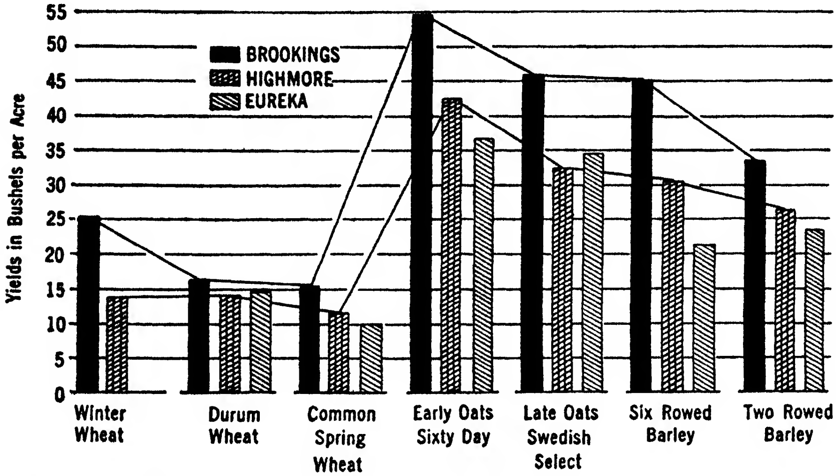


FIG. 16. Yields of cereal crops grown on variety test plats at Brookings, Highmore, and Eureka, South Dakota for the 21-year period, 1909–1929. (After Klages, 5.)

in the yields for the three South Dakota stations. It is evident that the yields of all crops considered were higher at Brookings than at

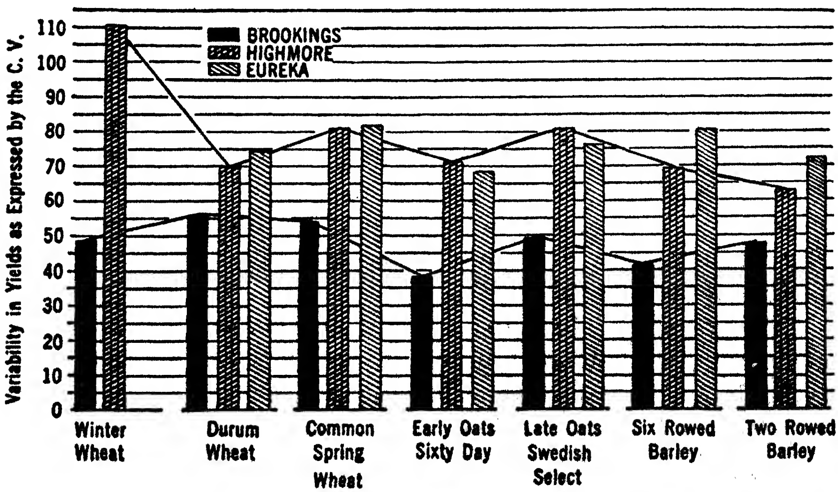


FIG. 17. Variability in the yields of cereal crops grown on variety test plats at Brookings, Highmore, and Eureka, South Dakota, for the 21-year period 1909–1929. (After Klages, 5.)

the two stations to the west. This is to be expected in view of the more favorable moisture relationships in the eastern than in the central parts of the state. Figures 16 and 17 show very definitely that the seasonal variability in the yields of the various crops considered is decidedly less at Brookings than at the two stations in the central portion of the state. This substantiates the theory that climatic conditions approach the ecological optimum to a higher degree in the eastern portion of South Dakota than in the central portion of the state. This condition holds true for all of the Great Plains states.

Yield and Variability Responses of Individual Crops in Eastern and Central South Dakota. The comparative yield and variability figures for crops grown in eastern and central South Dakota serve well to illustrate the performance of such crops in a transitional region grading from a section near the ecological optimum to a section farther distant from it.

The smallest differences in the yields of any of the crops at the three respective stations are those for durum wheat. The same is true for the differences in the degrees of variability of seasonal yields at the several stations.

Winter wheat was grown at only two stations, Brookings and Highmore. The differences in the yields and variability of such yields are very pronounced, primarily because of a greater amount of winterkilling in the central than in the eastern part of the state. Over a 23-year period, eight complete failures due to winterkilling are on record for Highmore as compared to only one for Brookings during the same period.

Attention is called to the relative performance of early and later maturing varieties of oats. It is evident from the higher average yields and the lower variability of such yields that early varieties of the Sixty Day type are better adapted to prevailing climatic conditions than later maturing varieties of the Swedish Select type. This is true for the eastern as well as for the central part of the state. In the northern part of the state, at Eureka, the difference in the yields of these two types is not of significance; at Brookings and Highmore the differences, however, are very pronounced. Even at Eureka, while the differences in the yields of Sixty Day and Swedish Select oats are not great, the yields of the latter variety show a considerably higher degree of variability.

Since, according to Harlan *et al.* (2), the six-rowed barleys of the Manchuria type yield best in the eastern portion of the northern Great Plains area, while the two-rowed barleys of the White Smyrna type are reported to do better in the western drier portion of this region, it was deemed advisable to include in this investigation performance records of representative two- and six-rowed varieties. With the exception of the returns at Brookings, the differences in the yields of the six- and two-rowed barleys are not very significant. It is interesting to note, however, that the coefficients of variability of the yields of these two types are lower in the central portion of the state for the barleys of the White Smyrna (two-rowed) than of the Manchuria (six-rowed) type. This suggests, even though the differences in the two values are not great enough to be statistically significant, that barleys of the White Smyrna type may, on account of their earlier maturity, be more drought-resistant, or in reality more drought-escaping, than barleys of the Manchuria type such as Odessa. It is common knowledge that White Smyrna will frequently produce at least a partial crop under seasonal conditions too severe for the survival of Odessa. On the other hand, White Smyrna lacks yielding ability under favorable conditions. Unpublished data by the author indicate a lower percentage of sterility in two-rowed barleys grown under high temperature conditions than in six-rowed barleys of the Manchuria type. This may help to explain the higher relative average yields of the two-rowed over the six-rowed varieties of barley in central South Dakota.

Only at Highmore were yields of flax available for a long enough period of time to be compared with those shown by the cereals. It was observed that the degree of variability shown by flax is considerably higher than that shown by any of the cereals. Flax, as brought out by Rotmistroff (7), has a relatively shallow root system; consequently, it is dependent on surface moisture or on precipitation during the growing season to a greater extent than the deeper rooted cereal crops. Furthermore, since young flax plants are rather tender and slower to establish themselves than the cereals, they are more susceptible to unfavorable environmental factors.

REFERENCES

1. Clements, F. E., *Plant Indicators.* Carnegie Inst. of Washington Pub. 290, 1920.
2. Harlan, H. V., M. L. Martini, and M. N. Pope, "Test of barley varieties in America," *U. S. Dept. Agr. Bull.* 1334, 1925.
3. Hutcheson, T. B., and K. E. Quantz, "The effects of greenhouse temperatures on the growth of small grains," *Jour. Amer. Soc. Agron.*, 9:17–21 (1917).
4. Klages, K. H. W., "Geographical distribution of variability in the yields of field crops in the states of the Mississippi Valley," *Ecology*, 11:293–306 (1930).
5. ———, "Geographical distribution of variability in the yields of cereal crops in South Dakota," *Ecology*, 12:334–345 (1934).
6. Miller, E. C., "Comparative studies of the root systems and leaf areas of corn and sorghums," *Jour. Agr. Res.*, 6:311–332 (1916).
7. Rotmistroff, W. G., *Das Wesen der Dürre, ihre Ursache und Verhütung.* Theodor Steinkoff, Dresden, 1926.
8. Shantz, H. L., and R. Zon, *Atlas of American Agriculture*, Part 1, Sec. E, "Natural vegetation." Washington, Govt. Printing Press, 1924.
9. Waller, A. E., "Crop centers of the United States," *Jour. Amer. Soc. Agron.*, 10:49–83 (1918).
10. Walster, H. L., "Formative effect of high and low temperatures upon growth of barley: a chemical correlation," *Bot. Gaz.*, 69:97–126 (1920).
11. Weaver, J. E., *Root Development in the Grassland Formation*, Carnegie Inst. of Washington Pub. 292, 1920.
12. ———, "Some ecological aspects of agriculture in the prairie," *Ecology*, 8:1–17 (1927).
13. ———, and J. W. Crist, "Relation of hardpan to root penetration in the Great Plains," *Ecology*, 3:237–249 (1922).

Chapter X

ADAPTATION

Adaptation Defined. Perhaps one of the best examples of the interaction of internal factors with external conditions may be found in a consideration of adaptation. Adaptation has been defined by numerous biologists; thus Lamarck [cited from Neger (9)] states that organisms are endowed with the ability to alter their organs quantitatively and qualitatively to meet the requirements of life. Herbert Spencer says life is that ability to bring the inner forces into adjustment with the exterior. Neger defines adaptation as that phenomenon by which plants react with the environment through alteration of their inner organization, this reaction leading to the production of more or less expedient characters.

Direct or Indirect Adaptation. In the older literature on adaptation the question of direct versus indirect causes for the production of characteristics enabling a plant to survive in a given environment was discussed at some length and at times with considerable feeling. The proponents of the theory of direct adaptation assumed that organisms were endowed with the ability to build up structures or alter their respective cycles of development to their own advantage as existing external conditions demanded. With the indirect conception of adaptation the development of such characteristics as may prove to be beneficial to the plant in its struggle for existence is considered strictly the result of chance.

According to Hayek (5) it may be considered immaterial whether adaptation characteristics (Anpassungsmerkmale) are produced by means of selection, through direct interaction with the environment, or by any other means. But, he continues, it will always be observed that members of greatly divergent systematic groups show identical or analogous adaptation characteristics when growing under similar external conditions. This is the same condition recognized by Schimper (12) in coining the term "climatic formation" as contrasted to the "edaphic formations."

The view of direct adaptation tends to lean too much to the teleological conception of nature. The close connection between the theory of direct adaptation and the Lamarckian theory of development of suitable characteristics in organisms is quite evident. The impossibility of direct adaptation is also brought out by De Vries (4).

> "If in order to secure one good novelty, nature must produce ten or twenty or perhaps more bad ones at a time, the possibility of improvement coming by pure chance must be granted at once. All hypotheses concerning the direct causes of adaptation at once become superfluous, and the great principle enunciated by Darwin once more reigns supreme. . . . Darwin's idea was that mutability took place in all directions and that the most favorable mutations were preserved."

De Vries (3) gave strong support to the theory of indirect adaptation according to which sudden discontinuous variates better adapted to a particular environment are produced. These sudden variates originate, according to De Vries, through mutations or, as taken by other authors, through fluctuating variability. From the viewpoint of indirect adaptation, selection during the struggle for existence decides the question of fitness. Thus, the environment in this view has not the "power of directly evoking in the organism an adaptive response" as was held by Warming (14). Rather, chance variates better able to cope with the factors of a given environment are able to multiply more rapidly and will in time replace those variates not so well adapted.

Selection for Fitness. The fact remains that variates, whatever their origin, be it through mutations, chromosome aberrations, hybridization, or other causes, are always present. The phenomenon of adaptation would, as stated by Lundegårdh (7), be indeed peculiar if organic life were fixed and unchangeable.

It is almost an axiom that plants growing naturally in a given environment exhibit a certain degree of fitness to the essential factors of their habitat. Those particular plants best suited by their structure or their functions gain the upper hand in the struggle for existence. Selection decides the question of fitness. As stated by De Vries (3), "natural selection is a sieve. It creates nothing, as is so often assumed; it only sifts. It retains only what variability puts into the sieve. Whence the material comes that is put into it, should be kept separate from the theory of its selection." According to

Crampton (2), "Selection is not regarded in any way originative but only as judicial, so to speak. As the members of any species present themselves at the bar, selection decides the question of survival or destruction on the basis of the conditions of correlation that is exhibited."

Crampton lays great stress on functional correlation of characters. "Separate characters do not serve directly as adaptive or inadaptive elements of the organism, but they do so only insofar as they exist in close or loose correlation with other structural or functional characteristics."

Stahl's Classification of Adaptations. Stahl (cited from Neger) grouped adaptations with respect to the selective factor or factors into three classes: (*a*) the converse, (*b*) the adverse, and (*c*) the biversale. In the converse type, the organism utilizes some particular factor of its habitat to its own advantage and to such an extent that it gains the upper hand over competing species. In the adverse type of adaptation the organism is through its functional or structural characteristics better protected against some dangerous element of its environment. In the biversale type the organism is considered as utilizing the favorable factors of the environment to its fullest extent, but at the same time it must be able to protect itself against some factor or factors working in excess.

Of the above three categories the last, or biversale, type no doubt offers the best explanation of how plants are able to adapt themselves to natural environments. It is difficult to find an environment where all conditions are at all times, for the entire vegetative rhythm of the plant, favorable or at the optimum. Again while a plant must have the ability to protect itself against some unfavorable factor in its environment it must of necessity utilize those factors favorable to growth; otherwise it could not survive. This is well summarized by Lundegårdh. In the uninterrupted struggle against external conditions and against competitors plants able to establish and maintain themselves are those best adapted to the environment by virtue of their particular structures and functions. The word "adapted" is taken as being descriptive. A particular plant or group of plants is better adapted than another if it is able to economize to a greater extent than its competitors the available energy and nutrients provided by the environment and at the same time is protected against unfavorable influences. Degrees of utilization

of favorable factors and protection against unfavorable or detrimental factors must be considered on a relative basis.

Adaptation in Relation to Scharfetter's Vegetation and Climatic Rhythms. Scharfetter's (11) terms, the "vegetation" and the "climatic rhythm," discussed in Chapter VII in relation to development, may be used to advantage in discussing the factors involved in adaptation. A plant cannot adapt itself to a given region unless it can so shape its vegetation rhythm as to fit into the particular climatic rhythm of that region. This does not mean that plants utilize all of the available climatic rhythm; often they do not, as for instance with the cereals in central Europe and in the eastern part of the United States. Spring wheat and oats in these sections mature during early summer, they do not take full advantage of the growing season. This does not mean that late-maturing varieties should be recommended for those regions, for other factors come into play on that point, such as ability to avert critical periods and ability to escape disease damage, as rust in wheat. A perfect harmony between the vegetation rhythm of a plant and the climatic rhythm of a particular region is hardly to be found; the climatic rhythm is made up of too many component parts for such a condition to be attained. Yet a high degree of harmony between these two rhythms is found in certain sections. The predominating importance of the corn crop in the Corn Belt of the United States and of the potato in northern Europe can be readily explained on the basis of the high degrees of harmony between the vegetation rhythms of these two crops and the prevailing climatic rhythms in the two areas. Both of these crops are outstanding from the standpoint of carbohydrate production. They make use of nearly the entire vegetation rhythm as against competing crops having their vegetative periods extending over only a portion of the climatic rhythm.

Critical Periods in Crop Production. Under conditions of the ecological optimum the harmony between the vegetation and climatic rhythms of plants may be considered complete. This condition, if realized at all, develops at rare intervals only. Under natural conditions it is to be expected that at certain stages in the growth cycle of a plant some factor of the environment either will be at the minimum or may be operating in excess of the growth requirements. It must also be recognized that during certain phases

of development the plant either makes more definite and exacting demands of the factors of the environment, or is more easily damaged by factors operating at either the minimum or the maximum rate. These periods of stress may be designated as critical. Van de Sande-Bakhuyzen (10) states "by the term critical period is meant the period in the life cycle of the plant during which the correlation between external conditions, i.e., rainfall or temperature, and the final yield is highest."

The question of critical periods in crop production is closely related to the general topic of crop risks or hazards. The plant passes during its course of development through easily vulnerable phases, the critical periods. Also the climates of certain areas have their favorable and unfavorable phases or as it may be stated their optimum and erratic periods. If climatic data for any given region are available for any considerable length of time, it is possible to establish a common or average sequence of climatic phenomena or the so-called phenological mean. The phenological mean would tend to put on a statistical basis the probabilities of the availability of the ecological factors such as moisture, temperature, and light at given intervals throughout the year and especially during the growing season. Where the degree of harmony between the vegetation and climatic rhythms is not complete, there is a possibility that the phase of development at which reductions in yields may most likely be expected may sometimes be shifted so that the critical period may fall at a time when better climatic conditions may prevail. Also a choice of variety may be made to shift the critical period or periods to a time when favorable climatic conditions may reasonably be expected. In a typical grassland climate a drought may be expected toward the middle of summer. The employment of early-maturing varieties, as has already been pointed out, may avert loss from such to-be-expected phases of the climatic rhythms. This would be a case of drought evasion. Martin and Sieglinger (8) give a good illustration of the above in their experiments with dates of seeding for different varieties of grain sorghums in the southern Great Plains area. At many stations a delay in the planting dates served to avoid critical periods. It was found especially desirable to shift the dates of flowering and seed development to late summer or early autumn when more moderate temperatures could be expected.

Critical periods may in limited instances be avoided by supplying artificially the factor of the environment which may happen to be at the minimum. Thus, water may be supplied by means of irrigation, or a mineral element may be supplied by a commercial fertilizer. Furthermore, special systems of cropping may be initiated to supply or to conserve the factor most likely to cut down yields. Critical periods due to the effects of disease may be avoided by the breeding of varieties or strains resistant to the particular disease encountered. The same may be said relative to insect damage.

Hazards in Crop Production. The question of hazards in crop production was discussed in relation to the geographical location of producing areas in the previous chapter. Diversification in the cropping program, where this is possible, may frequently be resorted to in order to stabilize production. Thus if the general cropping in a section, as in the northern Great Plains area, is of the spring-summer type, according to Spafford's (13) classification, the inclusion of a winter crop such as winter wheat, where its production is feasible, or winter rye, where winter conditions are too severe for wheat, will lead to a greater diversification of the cropping program. Such a change in the cropping system will not only serve to spread risks but will also enable producers to make better use of their labor and equipment.

Producers show a decided tendency to adjust their cropping enterprises with reference to the probable risks that may be expected. This may apply to physiological as well as to economic risks. Klages (6) pointed out one of the many illustrations that may be presented by showing the relationship between the rate of abandonment of winter wheat acreage in the state of South Dakota in any one year and the acreage planted for the following crop year. A close relationship between the acreage abandoned on May 1 of any one year and the acreage sown in September of that year is in evidence. This is brought out by the graphic presentation of these two factors in Fig. 18. Periods of high abandonment of acreage sown in fall, which are more or less synonymous to periods with winter conditions unfavorable to the survival of the crop, have in all years with the exception of the season of 1931 led to significant curtailments of acreage sown to winter wheat. Likewise a succession of years, or even separate seasons, with a low abandonment

resulted invariably in marked increases in winter wheat acreage. The high abandonment of acreage in 1931, of the crop sown in the fall of 1930, was due primarily to drought and factors incident to it rather than to heavy winterkilling. The above illustration is

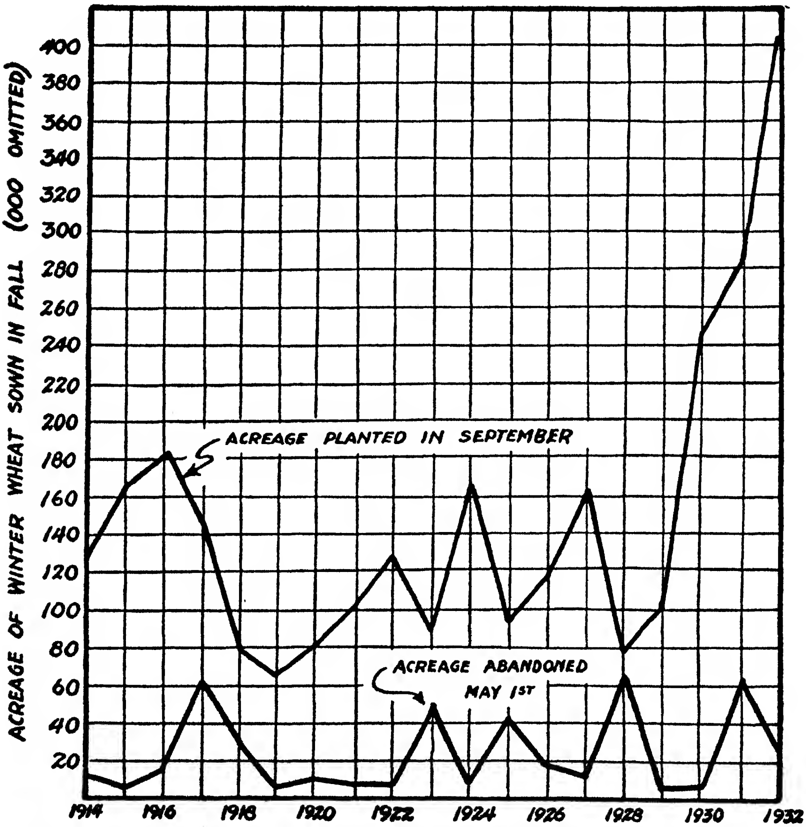


FIG. 18. Acreage of winter wheat in South Dakota abandoned on May 1 of any year and acreage sown in September of that year, 1914–1932. (After Klages.)

especially interesting insofar as it deals with a crop approaching its physiological limit of production.

Range of Adaptation. Some plants, crops, and varieties of crops are limited to rather restricted areas by their particular growth requirements or by economic conditions, while others are found or are grown over very extensive areas. These crops may be considered as having narrow or wide ranges of adaptation. Cotton is limited to those areas where the growing season is at

least 190 days. Alfalfa, on the other hand, is found from Canada to the Gulf and from the Atlantic to the Pacific. The areas producing rice or buckwheat are limited both by physiological and economic barriers, while wheat and corn are grown under a great variety of conditions. The reasons for this are definite; it is not necessary to go into them at this time.

It is well to note that some crop varieties have a narrow or limited, others a wide, range of adaptation. Thus, according to Clark and Bayles (1), the acreage of Turkey wheat, including that grown under the name of Kharkof and other synonyms, in 1929 comprised 15,925,677 acres, or 25.69 per cent of the total wheat acreage of the country. It was reported from 28 states. Red Wave was grown in 17 states over an area of 255,737 acres.

REFERENCES

1. Clark, J. A., and B. B. Bayles, "Classification of wheat varieties grown in the United States," *U. S. Dept. Agr. Tech. Bull.* 459, 1935.
2. Crampton, H. E., "On a general theory of adaptation and selection," *Jour. Exp. Zool.*, 2:425–430 (1905).
3. De Vries, H., *The Mutation Theory*, Vol. 1. Open Court Pub. Co., Chicago, 1909 (first published in 1903).
4. ———, *Species and Varieties and Their Origin by Mutation.* Open Court Pub. Co., Chicago, 1904.
5. Hayek, A., *Allgemeine Pflanzengeographie.* Gebrüder Borntraeger, Berlin, 1926.
6. Klages, K. H. W., "Winter wheat production in South Dakota," *S. D. Agr. Exp. Sta. Bull.* 276, 1933.
7. Lundegårdh, H., *Klima und Boden in ihrer Wirkung auf das Pflanzenleben.* Gustav Fischer, Jena, 1925.
8. Martin, J. H., and J. B. Sieglinger, "Spacing and date of seeding experiments with grain sorghums," *U. S. Dept. Agr. Tech. Bull.* 131, 1929.
9. Neger, F., *Biologie der Pflanzen.* Stuttgart, 1923.
10. Sande-Bakhuyzen, van de H. L., "Studies upon wheat grown under constant conditions," *Plant Physiology*, 3:1–30 (1928).
11. Scharfetter, R., "Phenology and agriculture," *Int. Rev. Sci. and Pract. Agr.*, 1:561–572 (1923).
12. Schimper, A. F. W., *Plant Geography upon a Physiological Basis.* Clarendon Press, Oxford, 1903.
13. Spafford, R. R., "Farm types in Nebraska as determined by climate, soil and economic factors," *Nebr. Agr. Exp. Sta. Res. Bull.* 15, 1919.
14. Warming, E., *Oecological Plant Geography.* Clarendon Press, Oxford, 1909.

PART III

THE ECOLOGICAL FACTORS

Chapter XI

GENERAL ASPECTS OF MOISTURE RELATIONSHIPS

The Relative Importance of Water in the Physiological Environment. The three most outstanding factors of the physiological environment are moisture, temperature, and light. The numerous factors of the environment are of necessity closely interrelated. Nevertheless, over large areas with similar temperature conditions the relative abundance of moisture available to plants has a more pronounced effect on the type of vegetation and on the adaptability of the area, or any portion of it, to crop production than does any other single factor of the environment. Robbins (26) states this emphatically in the following paragraph:

> "Water is the chief limiting factor in the growth of most crops. For the majority of crops, there is ample sunshine, and an abundance of oxygen and carbon dioxide in the air; the temperature of the air and soil is seldom seriously unfavorable; as a rule, there are sufficient nutrients in the soil; but the farmer, except in the most rainy sections of the country, is usually confronted at some time during the season with a shortage of water. This is particularly true in arid and semi-arid regions."

Warming (34) is not quite as emphatic as Robbins in stating that "The ecological importance of water to the plant is fundamental and almost surpasses that of light or heat." However, after dealing with the significance of water to the vital activities of plants, he comes out with a stronger statement: "It is . . . not surprising that no other influence impresses its mark to such a degree upon the internal and external structures of the plant as does the amount of water present in the air and soil (or medium), and that no other influence calls forth such great and striking differences in the vegetation as do differences in the supply of water."

Schimper (28) also emphasizes strongly the manifold influences of water on the expressions and appearances of plant life by stating

that "no factor affecting plant life is so thoroughly clear as the influence of water."

Thompson (32) states that "moisture is unquestionably the dominant factor in the production of crops and animals in South Africa. . . . It overrules all other aspects of farming enterprise in the Union and is closely related to the national welfare." Hann (11) supports the above statement with the following sentence: "The rainfall determines the productiveness of a country. Temperature and rainfall together are one of the most important natural resources of a country."

These various statements relative to the importance of the moisture factor are well summarized by McDougall (23). "It has long been recognized that the vegetative organs of different species were adapted to various conditions of water supply; and also that the occurrence of the larger plant formations was mainly determined by the moisture factor in the climate."

Moisture and Temperature Relationships. The close relationship existing between the moisture and temperature factors of the environment has been referred to on several occasions and will be further developed in the course of the discussion of these two important factors. From an ecological standpoint the intimate association of these two factors and also the light factor as related to the actual availability and economic utilization of water by plants is of prime importance.

The characteristics of adaptation to moisture relationships are usually very evident and apparent even to the layman. The internal as well as the external organizations of many plants are readily modified by variations in the amount of available moisture at their disposal. Some plants exhibit very wide ranges of adaptation with regard to the water factor; others again are quite specific in their requirements. The tall, leafy type of corn common in the heart of the Corn Belt, as compared with the progressively shorter and less leafy type of plant found in approaching the drier Great Plains area, offers a good illustration of both the range of adaptation and adaptation characteristics in the corn plant as related to the moisture factor. In the southern Great Plains Grain Sorghum Belt, the same factor finds expression in the types of sorghums produced, with the tall broad-leafed kafir in the eastern and the dwarf feterita and milo in the drier western sections of this area.

Adaptations to the water factor of the environment are usually more spectacular than adaptations to the temperature factor. Adaptations of crop plants to the water factor of the environment are in most instances concerned with a lack or scarcity of moisture during certain phases of development rather than with the presence of excessive amounts. This manifestation has, no doubt, much to do with the frequent and perhaps just designation of the moisture factor as being of primary importance.

The moisture factor is largely responsible for the designation of the type of climate based on natural vegetation such as the woodland, grassland, and desert types. As has been pointed out previously, the relative abundance of available moisture is intimately associated with the diversification of crop production in any given area. Abundance of moisture leads not only to a rich natural flora but also to a wide choice of crops that may be grown by the producer. Scarcity of moisture favors the development of the more or less hazardous one-crop system of production.

The Physiological Significance of Water to Plant Life. The fundamental significance of water to life is well brought out by the fact that all of the vital processes of both the plant and the animal cell take place in a water medium. The actual amount of water assimilated is very small. According to Maximov (22), even in moist climates not in excess of 2 to 3 grams of water for every 1,000 grams extracted from the soil are assimilated. In dry continental climates not more than 1 gram of 1,000 grams of water absorbed from the soil may be assimilated; the remaining 999 grams merely pass through the plant unchanged, to be dispersed into the atmosphere, but not without performing vital functions.

The importance of water in relation to the development of land plants is brought out in an interesting fashion in the following paragraph taken from the introduction of Maximov's book *The Plant in Relation to Water:*

> "Organic life in all probability originated in water, and all living cells and tissues of animal as well as plant organisms must be saturated with water in order to carry on their normal life activities. The migration from water to dry land represented a great step forward in the development of the organic world. But the change of conditions threatened the organism with the danger of desiccation and the consequent loss of its vital properties. The migration, therefore, was

necessarily accompanied by the development of numerous adaptations, which allowed the cell to be saturated with water under the new conditions, as it was during its life in an aquatic medium."

Moisture as a Climatic and Edaphic Factor. The amount of water present in a soil at any given time has a direct influence on the concentration of the soil solution and constitutes one of the main factors determining the ease with which water and the soluble nutrients can be absorbed by the roots of plants. In this respect, soil moisture becomes an edaphic factor. Soil moisture in relation to its numerous direct and indirect influences can, without doubt, be designated as one of the most significant factors determining the subterranean habitats of plants.

Soil moisture is important not only from the standpoint of the immediate responses it may evoke but also from the standpoint of its accumulative effects. The amount and more specifically the efficiency of the precipitation received in any given locality determine more than any other single factor the characteristics of the soil itself. The continued percolation of water through the soil in humid areas or the absence of the leaching process in arid sections is associated to a high degree with the development of specific soil characteristics.

Kellogg (15) in stating the factors of soil genesis brings out that any soil in relation to its development is to be considered as a function of climate, vegetation, relief, age, and parent material. Moisture and temperature make up the important climatic factors. These two factors are interrelated as will be brought out in Chapter XIII in connection with the presentation of indices of moisture efficiencies. The relative abundance, intensity, and form of the precipitation not only influence the type and luxuriance of the vegetation of a region but also are definitely associated with the relief, that is, with the development of the topographical and drainage features.

Marbut (20) classified soils into two major groups on the basis of the presence or absence of calcium carbonate accumulations in some horizon of the soil, usually in the subsoil. The pedocals or the lime-accumulating soils are found in arid or semiarid while the pedalfers or nonlime-accumulating soils occur in humid areas. In the United States the dividing line between these two major groups of soils extends from western Minnesota, through north-

western Iowa, southeastern Nebraska, east-central Kansas, central Oklahoma, and east-central Texas to the Gulf, with the pedalfers to the east and the pedocals to the west of the line.[1] The effects of climatic conditions in general and the moisture factor in particular on the location of this boundary line are self-evident. While the accumulation of lime in pedalferic soils is effectively prevented by the more or less continuous percolation of water through these soils and the resulting leaching, they show, nevertheless, that iron,

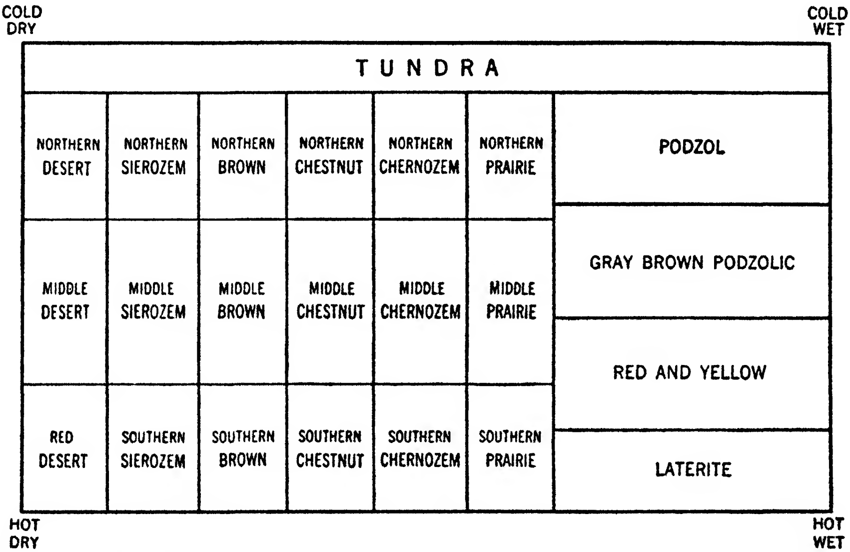


FIG. 19. Relative positions of the important zonal groups of soils in relation to the moisture and temperature factors. (After Kellogg.)

aluminum, and the soil colloids have been shifted to a lower horizon and accumulated during the process of soil-profile development in temperate regions. The place of accumulation is marked by the formation of hardpans, the so-called "ortstein," of podzolized soils in northern areas. Under tropical high-temperature conditions lateritic soil types are formed in which iron and aluminum remain in the surface horizons while the silica is moved to lower horizons of the profile. This accounts for the typical red color of those soils.

Figure 19 gives an idealized distribution of the zonal groups of soils with respect to variations in climate, moisture, and temper-

[1] See Fig. 63, Chapter XXI.

ature and the resulting natural vegetation. Thornthwaite (33) produced a similar figure with the employment of his precipitation and the temperature efficiency indices. Lang (16) used average annual temperatures and his rain factor in constructing his graphic presentation of the interrelations of climatic factors to the development of soil characteristics.

Ecological Classification of Plants According to Their Water Relationships. Early in the history of ecology, because of the striking differences in vegetation produced by the water factor in the environment, plants were divided into more or less well-defined groups according to their water relations. Warming's classification of vegetation types into three groups, the hydrophytes, mesophytes, and xerophytes, is generally accepted. Plants growing in "fresh" water or in very humid habitats are hydrophytes. The mesophytes, or typical land plants, grow under medium climatic and soil conditions. Plants "capable of enduring without injury a prolonged period of drought," using Maximov's definition, are xerophytes.

Schimper used the terms "hygrophytes," "tropophytes," and "xerophytes" for the designation of vegetation types of habitats of increasing degrees of dryness. They are practically synonymous with the groups established by Warming.

Maximov points out and presents data to show that "the limits of these groups are naturally ill defined, and in practice it is sometimes difficult to decide to which group a given plant shall be assigned."

Hydrophytes. The hydrophytes grow either in a water environment or in places where the air is so moist that a too rapid loss of water from the aerial organs is hindered.

Mesophytes. The mesophytes or common land plants take an intermediate position between the hydrophytes and the true xerophytes. Practically all crop plants can be assigned to this group. Rice is the only cereal that may be classified as a hydrophyte. The sorghums, more particularly the grain sorghums, are the only crop plants with characteristics approaching the true xerophytes. But even this group of plants falls short of satisfying the requirements of the genuine xerophytes in that they are not able to endure prolonged periods of drought without injury. According to the terminology advanced by Kearney and Shantz (14), crop plants grown in dry areas, as well as the desert ephemerals, are either drought-escaping or drought-evading.

Xerophytes. An interesting and controversial literature is available on the question of which particular plants should be designated as true xerophytes. The older viewpoints on this topic are well represented by the following paragraph from Pfeffer (25).

> "Many plants are compelled to use the little water they can obtain in the most economical manner possible, and in such cases adaptations to protect them from excessive transpiration are most markedly developed. Indeed the special shape and structure of typical xerophilous plants have mainly this importance, for in order that they may cope with the conditions under which they exist, the surface-area is reduced as far as possible, although this places the plant at a disadvantage in other ways. Thus the regulatory diminution of transpiration which becomes necessary when the supply of water is limited involves a hindrance to gaseous exchange, and thus prevents the full functional activity of the chlorophyll-apparatus from being exercised."

Kamerling (13) proposes that plants designated as true xerophytes should be limited to those plants expending not more than from 2 to 10 per cent of their water content daily. This statement obviously can be applied only to the behavior of those plants under conditions not found infrequently, "when the supply of water is limited," otherwise the term "xerophytes" could be applied to but few plants.

The newer views regarding the structures and organization of xerophytes are championed by Maximov. He points out that, even though xerophitic plants are found in dry habitats, they are as a class not compelled to reduce transpiration. Maximov goes into considerable detail to make the point that a low intensity of transpiration is not characteristic of xerophytes.

It is interesting to note, however, that in making this statement and in advancing evidence to support it, he does not differentiate between the behavior of the plants relative to their intensities of transpiration for times when moisture is, and is not, available for their use. Xerophytes are defined as "plants capable of enduring without injury a prolonged period of drought." The reader will find no objections to this definition or to the one advanced by Delf (8), who defines "xerophilous plants as those which with the help of certain structural modifications can continue to perform their normal functions when exposed to climatic conditions involving atmospheric or edaphic drought, or both." The fact remains

that moisture during periods of "drought" is either only slowly or not at all available for the use of plants. Consequently plants able to survive such periods of stress must be able to preserve life either by certain "structural modifications" or special characteristics of their protoplasm. Maximov himself comes out with a statement to the effect that "the chief importance . . . of the high osmotic pressures found in desert plants is during wilting, when there is real danger of excessive loss of moisture." In this connection it is well to point out the behavior of hardy varieties of winter wheat. Newton (24) and also Martin (21) show that the winter-hardiness of certain varieties of wheat is associated with the relative quantities of hydrophilic colloids, measured by "bound water," contained in their tissues. The presence of these hydrophilic colloids may account, in part, for differences in resistance to desiccation found in certain varieties when exposed to physiological drought.

The adaptation characteristics of all xerophytes are by no means alike. "An examination of the physiological, anatomical, and morphological peculiarities of xerophytes leads us to the conclusion," states Maximov, "that the same results, *i.e.*, adaptation to life in a dry habitat, may be attained in diverse ways. Within the group of xerophytes, therefore, distinct and even contrasting types must be recognized."

Considerable confusion can be avoided in a discussion of the characteristics of xerophytes by excluding from this group of plants the cacti and similar succulents, as well as the desert ephemerals.

The physiological peculiarities of the cacti and similar succulents relative to respiration, assimilation, and transpiration are not characteristic of other desert plants. The respiratory processes of these succulents differ from those of other plants in that organic acids are formed in the dark which later decompose to form carbon dioxide. In ordinary plants, the carbon dioxide is dispersed into the air; in the cacti it is utilized in the process of carbon assimilation, without leaving the chlorenchyma. This results in a material saving of moisture. Livingston (17) and Shreve (30) called attention to the fact that the relative transpiration of the cacti is lower in the daytime than at night. These peculiarities of the cacti and certain other succulents separate them into a special ecological type. Their low osmotic pressures and not infrequent superficial

root systems make them more like the epiphytes (air plants) than the true xerophytes in that they are primarily dependent on water absorbed during or soon after rains.

The desert ephemerals are annual plants which spring up after the occurrence of rains but soon succumb as moisture in the surface soil becomes less available. These plants do not differ from ordinary mesophytes; they are simply drought-escaping.

Factors Interfering with the Absorption of Water by Plants. Schimper lists four factors impeding the absorption of water by plants: (*a*) low water content of the soil, (*b*) abundant supplies of soluble salts in the soil, (*c*) the presence of humic acids in the soil, and (*d*) low soil temperature. To these may be added the lack of oxygen in soils with excessive amounts of water.

As the thickness of the water film around individual soil particles is reduced it becomes increasingly difficult for the root hairs to remove water from the soil. Eventually, as the wilting coefficient of the soil is approached, the force with which the water is held around the soil particles becomes so great that the root hairs, the absorbing cells of the plant, are unable to overcome it. Since the plant continues to transpire water, it wilts. The wilting coefficients of different soils differ materially; they are directly associated with the water-holding capacity of the soil. The wilting coefficients of soils may be determined physiologically. Generally, however, they are calculated from either the moisture equivalents or the hygroscopic coefficients of soils (Briggs and McLane, 2).

Aside from the fact that certain soluble salts may be directly toxic to the roots of plants, a high concentration of soluble salts in the soil definitely impedes the absorption of water by plants in relation to the extent to which they serve to increase the concentration of the soil solution. Certain plants can overcome this obstacle by means of high concentration of their cell saps. Many desert plants, as Fitting (9) and also Maximov and his associates have shown, are characterized by the ability to produce high osmotic pressures and as a result can develop a suction force sufficient to overcome the resistance to absorption of even relatively concentrated soil solutions.

Schimper first advanced the hypothesis of "physiological dryness" of bog soils by suggesting that the presence of humic acids interferes with the absorption of water. Dachnowski (6 and 7) substituted

soil toxins for humic acids, while Shröter (29) regarded the high water-retaining capacities of bog and peat soils as the chief factor bringing about physiological dryness. Lundegårdh (19) points out that trees have difficulty in establishing themselves on bog and peat soils, not because of the excess of water, but rather because of the lack of oxygen and the surplus of carbon dioxide.

The temperature of the soil has a direct bearing on the rate of water absorption. Frozen soils, and for nonhardy plants even cold soil, are physiologically dry.

The Wilting of Plants. Not infrequently plants lose greater quantities of moisture to the surrounding atmosphere than they are able, for the time being, to absorb from the soil. Such a condition leads to a more or less marked water deficit in the plant. Under conditions of a high saturation deficit of the atmosphere in immediate contact with the plant the loss of water may be so great that an optimum water balance cannot be maintained by plants even though the soil may contain an abundance of moisture. Such atmospheric droughts are encountered during periods of hot, dry winds. Pronounced water deficits in plants result most commonly from a scarcity of available water in the soil; they become critical when a slow rate of absorption is combined with a high loss of water by increased transpiration. It must be kept in mind that increased transpiration, while rapidly diminishing the water content of plants, also leads to significant increases in leaf suction and absorption of water when it is available. Also, the aerial portions of plants are not entirely without certain protective devices against excessive losses of moisture. Instituted economies in water utilization are effective, however, only within rather well-defined and limited ranges.

The water content of plants is reduced whenever the loss of water through transpiration is in excess of that absorbed. Increasing water deficits are usually accompanied by a perceptible loss in turgor, though not enough in the initial stages to produce definite wilting. Livingston and Brown (18) refer to such conditions of decreased water content and partial loss of turgor, up to but not including definite wilting, as "incipient drying." Such *incipient drying* serves to increase the osmotic pressure of the cells of leaves. Furthermore, as the vapor pressure in the intercellular spaces of the leaves is reduced by continued high rates of transpiration,

the loss of water from leaves is in part slowed down by this reduction in vapor pressure even before the stomata are closed.

With the continued giving off of water by plants, especially when the reserve in the soil is exhausted to the extent that the losses cannot be compensated, the plant soon reaches the stage of *transient wilting*. This stage is marked by a partial folding up or collapse of the leaves and tender tissues. Unless conditions either favoring absorption of water or serving to reduce transpiration are provided at this point to restore the water balance to a normal level, the final stage, *permanent wilting*, is soon reached. The leaves transpiring most rapidly show the greatest water deficits, and since they also possess the greatest power of suction they draw water from other portions of the plant. By successive stages the upper and younger leaves withdraw water from the older ones, from the growing points of the stems, and eventually from the absorbing regions of the roots. As a result all parts of the plants are to a considerable extent deprived of water.

Transient wilting occurs in plants at rather frequent intervals. While it is instrumental in slowing down rates of assimilation of carbon dioxide, it has mostly temporary effects; with the restoration of moisture in the soil or with a return of conditions less favorable to rapid transpiration a proper water balance is reestablished, turgor regained, and growth proceeds at fairly normal rates. The difference between transient and permanent wilting is, according to Maximov, one of degree rather than of kind. Plants having their water content reduced to the point of permanent wilting recover but slowly and then only under the most favorable soil moisture and environmental conditions. Even though recovery takes place under exceptional conditions, the wilting has lasting detrimental effects. Successive repetitions of wilting are especially detrimental to plants. Caldwell's (5) experiments have shown that more water remained in soils with repeated wilting than after an initial wilting of plants. This is no doubt due to a partial destruction of the root hairs.

Drought. The term "drought" is used freely by both agronomists and laymen. While the term may be readily defined in the descriptive sense, the exact designation of droughts in the quantitative sense is fraught with difficulties in that water deficits in plants and the causes for such reductions in water content may be

numerous and varied depending on environmental conditions and differences in the reactions of plants during the various stages of development.

Smith (31) defines drought as "a condition under which plants fail to develop and mâture properly because of an insufficient supply of moisture." Rotmistroff (27) defines the term as a temporary lack of moisture in the soil, which is felt by the plant and interferes with the normal course of the life processes. Blair (1) checks closely with the above authors by designating drought as "a continuous lack of moisture, so serious that crops fail to develop and mature properly."

Maximov speaks of atmospheric and soil drought. Since reductions in the water content of plants severe enough to cause material damage may be produced by hot dry winds, even when an abundant moisture supply is found in the soil, this point is well taken. Wilting due to atmospheric drought is usually temporary. It may result from either an inadequate root system or sheer physical inability to conduct water fast enough to compensate the losses from the leaves and tender portions of plants during periods of stress. Atmospheric drought occurs especially in areas near the physiological moisture limits of production. Extensive dry areas with sparse vegetative covers favor the occurrence of dry winds and the development of atmospheric drought. The hot dry winds of the Great Plains area and the Italian sirocco winds are notable examples.

Soil drought is most disastrous to crop plants when occurring at times of greatest need of water such as during the grand period of growth and well-defined critical periods. It is at such times that the plant makes its greatest demands for the expansion of its tissues and the building up of structures correlated with yield performance. Plants do not differ materially in the amounts of moisture that they are able to withdraw from a given soil.

Droughts occur more frequently in minimal than in optimal areas. But slight deviations from the normal receipts, or in instances increases in the utilization of moisture by plants as a result of the intensification of environmental factors, may lead to severe reductions in yields in the minimal areas, while significantly greater deviations from the to-be-expected rainfall may have no material influence on the growth of plants in optimal areas. Droughts, on

the other hand, are likely to occur at intervals even in humid climates. "Periods of excessive and deficient rainfall," states Holzman (12), "are normal to all climates."

It is necessary to take into consideration the normal rainfall cycle of a region in connection with the designation of droughts. In areas with a Mediterranean type of climate the occurrence of dry periods toward the middle of summer, severe enough to inhibit the growth of crop plants, is a normal phenomenon. This condition is met with in the Pacific Coast states. Crop production is more or less arranged to correspond with the prevailing type of rainfall distribution. While influencing the cropping systems, such reoccurring summer droughts do no particular damage. The other extreme is found when the expected rainfall fails to make its appearance. If such periods coincide with the critical periods of the crops grown in the area reduced yields and even complete failures may result. The term "drought" should therefore be applied to moisture deficiencies deviating sufficiently from the phenological mean to interfere with the normal life processes of plants to the extent that the balance of nutrition is shifted far enough in an unfavorable direction to result in material reductions in crop yields.

Excessive Moisture and Humidity. Cardinal points of vital activity apply to the moisture factor as well as to the temperature factor in connection with which they are most commonly employed. Even though the points may not be as specific when applied to water as to temperature relationships, it is nevertheless permissible to speak of minimal, optimal, and maximal moisture conditions.

Excessive amounts of water in the soil interfere with the biological processes and limit the amount of oxygen. The lack of oxygen, in turn, initiates numerous detrimental chemical processes such as reductions and the formation of substances toxic to the roots of plants. An optimum soil moisture content must allow for proper aeration. The continued percolation of water through a soil may also lead to leaching and the removal of nutrients, especially nitrogen, in sufficient quantities to interfere with the normal growth of plants.

Excessive rainfall during critical periods may have decided detrimental effects as during the germination and emergence of leguminous plants and during flowering. Heavy rains interfere

not only with the oxygen relationships of soils but may compact the surface of the soil so as to make emergence of dicotyledonous and other tender plants difficult. Excessive precipitation also interferes with the pollination of fruits, oats, and sorghums.

High temperatures in connection with intense sunlight, air currents, and a low atmospheric humidity lead to high rates of transpiration and losses of water from the tissues of plants. The transpiration ratios of plants of humid areas are significantly lower than those of the same plants grown in arid regions. Thus a given amount of water will, other factors being equal, produce a greater amount of dry matter in humid than in arid areas. Some physiologists, notably Haberlandt (10), have expressed the opinion that a very high atmospheric humidity may reduce transpiration to a point detrimental to the plant. Lundegårdh points out that "a continued saturation of the air, and a continued turgescence of leaf cells, exert an unfavorable influence upon the uptake of salts and upon translocation."

Bürgerstein (4) indicates that the ratio of transpiration in the tropical rain forests may be sufficiently high for the requirements of the plants. It may be assumed that the transpiration ratios of crop plants even when grown in humid climates are high enough so as not to interfere with other plant functions.

A combination of high atmospheric humidity and temperature is very effective in excluding certain plants from areas where such conditions prevail. The reason for this is pathological rather than physiological in that such environments are exceptionally favorable to the development of definite plant diseases such as rusts, mildews, scabs, and leaf spots. The conditions for the development of such pathogens are so ideal under humid high-temperature environments as very effectively to exclude wheat, barley, alfalfa, and clover from such humid megathermal areas. The above plants and others become important crops in humid areas with more moderate temperatures or in regions with high temperatures but relatively low atmospheric humidities.

Another factor to be considered is the curing and storing of crops after they have been produced. The curing of hay represents a serious problem in wet areas. One contributing reason for the overwhelming importance of rice as a cereal crop in humid, tropical areas is that it lends itself better to storage under existing

conditions than wheat or other cereals, the nature of the endosperm being such that it does not absorb moisture as readily as that of the wheat kernel.

REFERENCES

1. Blair, T. A., *Weather Elements.* Prentice-Hall, New York, 1937.
2. Briggs, L. J., and J. W. McLane, "Moisture equivalent determinations and their application," *Proc. Amer. Soc. of Agron.*, 2:138–147 (1910).
3. ———, and H. L. Shantz, "The relative wilting coefficients for different plants," *Bot. Gaz.*, 53:229–235 (1912).
4. Bürgerstein, A., *Die Transpiration der Pflanzen.* Verlag von Gustav Fischer, Jena, 1904.
5. Caldwell, J. S., "The relation of environmental conditions to the phenomenon of permanent wilting in plants," *Physiol. Res.*, 1:1–56 (1913).
6. Dachnowski, A., "The toxic property of bog water and soil," *Bot. Gaz.*, 46:130–143 (1908).
7. ———, "Physiologically arid habitats and drought resistance in plants," *Bot. Gaz.*, 49:325–339 (1910).
8. Delf, M., "The meaning of xerophily," *Jour. Ecol.*, 3:110–121 (1915).
9. Fitting, H., "Die Wasserversorgung und die osmotischen Druckverhältnisse der Wüstenpflanzen," *Zeitschr. f. Bot.*, 3:209–275 (1911).
10. Haberlandt, F., "Anatomisch physiologische Untersuchungen über das tropische Laubblatt," *Sitzb d. K. Akad. der Wissensch. in Wien*, 101:785 (1892).
11. Hann, J., *Handbook of Climatology*, trans. German by R. DeCourcy Ward, Part I. "General climatology." Macmillan, New York, 1903.
12. Holzman, B., "Sources of moisture for precipitation in the United States," *U. S. Dept. Agr. Tech. Bull.* 589, 1937.
13. Kamerling, Z., "Welche Pflanzen sollen wir 'Xerophyten' nennens." *Flora*, 106:433–454 (1914).
14. Kearney, T. H., and H. L. Shantz, "The water economy of dry land crops," *U. S. Dept. Agr. Yearbook* 1911, 351–361.
15. Kellogg, C. E., "Development and significance of the great soil groups of the United States," *U. S. Dept. Agr. Misc. Pub.* 229, 1936.
16. Lang, R., *Verwitterung und Bodenbildung als Einführung in die Bodenkunde.* Stuttgart, 1920.
17. Livingston, B. E., "Relative transpiration in Cacti," *Plant World*, 10:110–114 (1907).
18. ———, and W. H. Brown, "Relation of the daily march of transpiration to variations in the water content of foliage leaves," *Bot. Gaz.*, 53:309–330 (1912).

19. Lundegårdh, H., *Environment and Plant Development*, trans. and ed. from 2d German ed. by E. Ashby. Edward Arnold & Co., London, 1931.
20. Marbut, C. F., *Atlas of American Agriculture*, Part III, Soils of the United States. U. S. Govt. Printing Office, Washington, 1935.
21. Martin, J. H., "Comparative studies of winter hardiness in wheat," *Jour. Agr. Res.*, 35:493–535 (1927).
22. Maximov, N. A., *The Plant in Relation to Water*, authorized trans. by R. H. Yapp. Allen and Unwin, London, 1929.
23. McDougall, E., "The moisture belts of North America," *Ecol.*, 6:325–332 (1925).
24. Newton, R., "A comparative study of winter wheat varieties, with especial reference to winter-killing," *Jour. Agri. Sci.*, 12:1–19 (1922).
25. Pfeffer, W., *The Physiology of Plants*, trans. German by A. J. Ewart, Vol. I. Clarendon Press, Oxford, 1900.
26. Robbins, W. W., *Principles of Plant Growth*. Wiley, New York, 1927.
27. Rotmistroff, W. G., *Das Wesen der Dürre, ihre Ursache und Verhütung*, trans. Russian by E. von Riesen. Theodor Steinkopff, Dresden, 1926.
28. Schimper, A. F. W., Plant Geography upon a Physiological Basis, trans. German by W. R. Fisher. Clarendon Press, Oxford, 1903.
29. Schröter, C., *Das Pflanzenleben der Alpen*. Zurich, 1908.
30. Shreve, E., "An analysis of the causes of variations in the transpiring power of Cacti," *Physiol. Res.*, 2:73–127 (1916).
31. Smith, J. W., *Agricultural Meteorology*. Macmillan, New York, 1920.
32. Thompson, W. R., *Moisture and Farming in South Africa*. Central News Agency, South Africa, 1936.
33. Thornthwaite, C. W., "The climates of North America according to a new classification," *Geog. Rev.*, 21:633–655 (1931).
34. Warming, E., *Oecology of Plants*, trans. German by P. Groom and I. B. Balfour. Clarendon Press, Oxford, 1909.

Chapter XII

QUANTITATIVE ASPECTS OF MOISTURE RELATIONSHIPS

Vapor in the Atmosphere. The atmosphere contains many gaseous constituents; the proportions of nitrogen, oxygen, carbon dioxide, and other gases remain fairly constant; but the water vapor present is extremely variable. The other gases are individually of no special meteorological significance, but the water vapor is very important in that not only the direct receipts of rainfall but also the losses of moisture from either the soil or plants are greatly influenced by it. The amount of moisture present in the atmosphere at any given time may be expressed as vapor pressure, absolute humidity, relative humidity, or on the basis of the saturation deficit.

Vapor pressure and dew point. When water vapor escapes into space and mixes with the other gases of the air, it exerts a pressure in all directions, as do the other gases. This is known as the vapor pressure of the air. The force exerted depends upon the concentration of the vapor or upon the number of molecules per unit of volume. At the saturation point the number of molecules returning to the liquid becomes equal to the number escaping. Consequently the net evaporation is zero. At any given temperature the saturation vapor pressure has a definite, fixed value, but the values change rapidly with changing temperatures. Vapor pressure is commonly expressed in the same units as total air pressure, that is, either in millibars or in inches or millimeters of mercury, referring to the length of the barometer column that the partial pressure of the water vapor would sustain. The saturated vapor pressure at 0, 25, 50, 75, and 100°F is 0.038, 0.130, 0.360, 0.866, and 1.916 inches, respectively.

The temperature at which saturation occurs is called the dew point. Air having a vapor pressure of 0.130 inches has a dew point at 25°F at a barometric pressure of 30.00 inches. When the vapor

is cooled below its dew point, some of it is changed from a gas to the liquid form, that is, it condenses.

Absolute humidity. The amount, or the actual mass, of water vapor present in the air at any given time can be measured by aspirating a measured quantity of air through a hygroscopic substance, weighing the substance before and after. The increase in weight corresponds to the absolute humidity; it can be expressed in grains per cubic foot of air. Air is saturated when it contains 1.9 grains of water vapor when the temperature is 30, 4.1 with a temperature of 50, 8.0 with a temperature of 70, and 14.7 grains per cubic foot when the temperature is 90°F.

The absolute humidity and vapor pressure refer to one and the same phenomenon, namely, the actual amount of water vapor present in the air. The difference is only in the manner of expression. Since the determination of vapor pressure and the absolute humidity require elaborate instruments, they are not ordinarily given by most weather stations.

Relative humidity. The relative humidity of the air refers to the ratio, expressed as a percentage, between the amount of moisture in the atmosphere and the amount that could be present, without condensation, at the same temperature and under the same pressure. Thus heating a given volume of air, as in a room, does not increase its absolute but greatly reduces its relative humidity. The ~~increased~~ temperature increases the vapor-holding capacity of the air.

The relative humidity of the atmosphere is readily determined. The most common instrument is the sling psychrometer. This consists of two thermometers fastened to a metal strip which whirls upon a pivoted handle or by means of a geared mechanism, the whirling table. The two thermometers are alike, but one has a thin piece of clean muslin tied around the bulb. This bulb is dipped into clean water before the instrument is whirled. The difference in the temperatures of the dry- and wet-bulb thermometers is directly proportional to the dryness (vapor pressure) of the air. The relative humidity of the air may then be read directly from the prepared psychrometric tables of the United States Weather Bureau. Records of relative humidity can be obtained from hair hygrometers and hygrographs, that is, hygrometers with recording mechanisms.

Hann (7) summarizes the application and relative significance of the relative humidity as follows. "For purely climatological purposes the relative humidity is unquestionably the most convenient expression for the amount of water vapor in the air. When we describe the air as being damp or dry, we are usually speaking quite unconsciously of the relative humidity."

Relative and absolute saturation deficit. When the atmosphere has a relative humidity of 65 it is carrying 65 per cent of its possible capacity of water vapor at the given temperature and pressure; an additional 35 per cent of water vapor would saturate the air. This additional amount of vapor required to bring the air up to the saturation point is referred to as the saturation deficit. The absolute saturation deficit in terms of millimeters of mercury is expressed by the difference between the observed vapor pressure and the maximum vapor pressure possible at the temperature then prevailing.

Forms of Precipitation. The form of precipitation is dependent on the temperature at which condensation takes place and the conditions encountered as the particles pass through the air. The term "precipitation" refers to measurable moisture received, whether in the form of rain, snow, dew, hail, graupel, sleet, or glaze, and is expressed either in inches or in millimeters.

Rain is by far the most important form of precipitation not only in amount but also in relation to its effects on vegetation. In areas of winter precipitation receipts of snow are of considerable importance, as a matter of fact so much so in northern areas as to be definitely associated with crop yields. Snow provides in such areas not only moisture but significant protection to perennial and winter annual plants.

Dew and even light rains, insofar as they moisten only the leaves of plants or the surface of the soil, are of little value to plant life except that they decrease for the time being the rate of either transpiration or evaporation.

While hail does provide moisture, it has an injurious effect on plants and especially crop plants if occurring during the vegetative season. Hail damage is dependent on the intensity of the hail storm and on the stage of development of the plants subjected to it. It is most detrimental if occurring during the grand period of growth, but in the cereals great damage can also be inflicted during the

mature stage or immediately prior to maturity. Figure 20, taken from Ward (20), shows the average number of days with hail during the frostless season in various sections of the United States. The Great Plains and the Rocky Mountain regions show the greatest hail hazards. Hail is generally a warm-season phenomenon and falls in connection with thunderstorms. Condensation frequently

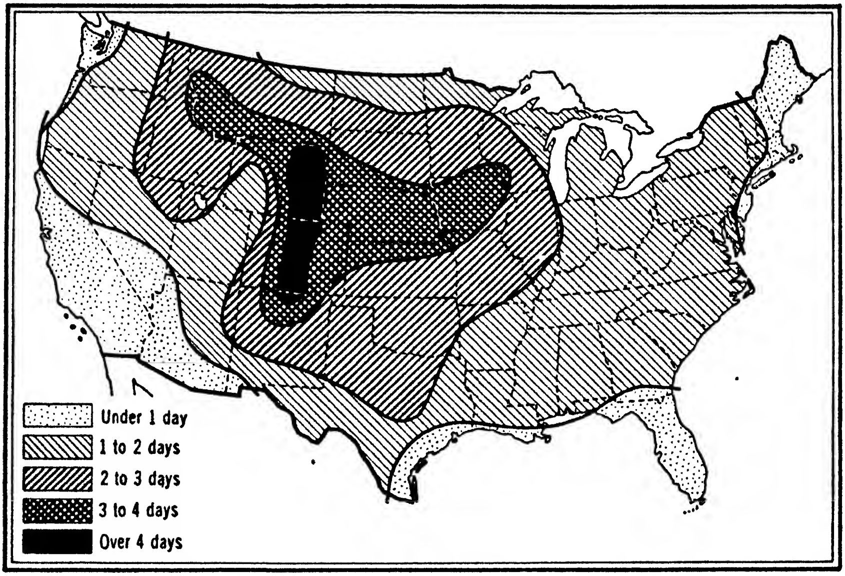


FIG. 20. Average annual number of days with hail during the frostless season. (Reproduced from Ward, *The Climates of the United States*, by permission of Ginn and Company.)

begins as rain, but the drops instead of falling may be carried upward by rapidly ascending currents of air into cloud areas where temperatures are below freezing. Blair (2) points out that the distinct layers of snow or ice frequently observed in hailstones are acquired by successive upward and downward movements of developing stones. Various attempts have been made by investigators to evaluate the extent of hail damage either by direct observation or by means of simulated injuries. Schander (16) and also Eldredge (5) worked with the cereal crops; Dungan (4), Hume and Franzke (9), and Garber and Hoover (6) with corn; and Klages (12) with flax.

Soft, moist snowflakes, falling through gusty air, are sometimes blown together and reach the ground as relatively soft pellets.

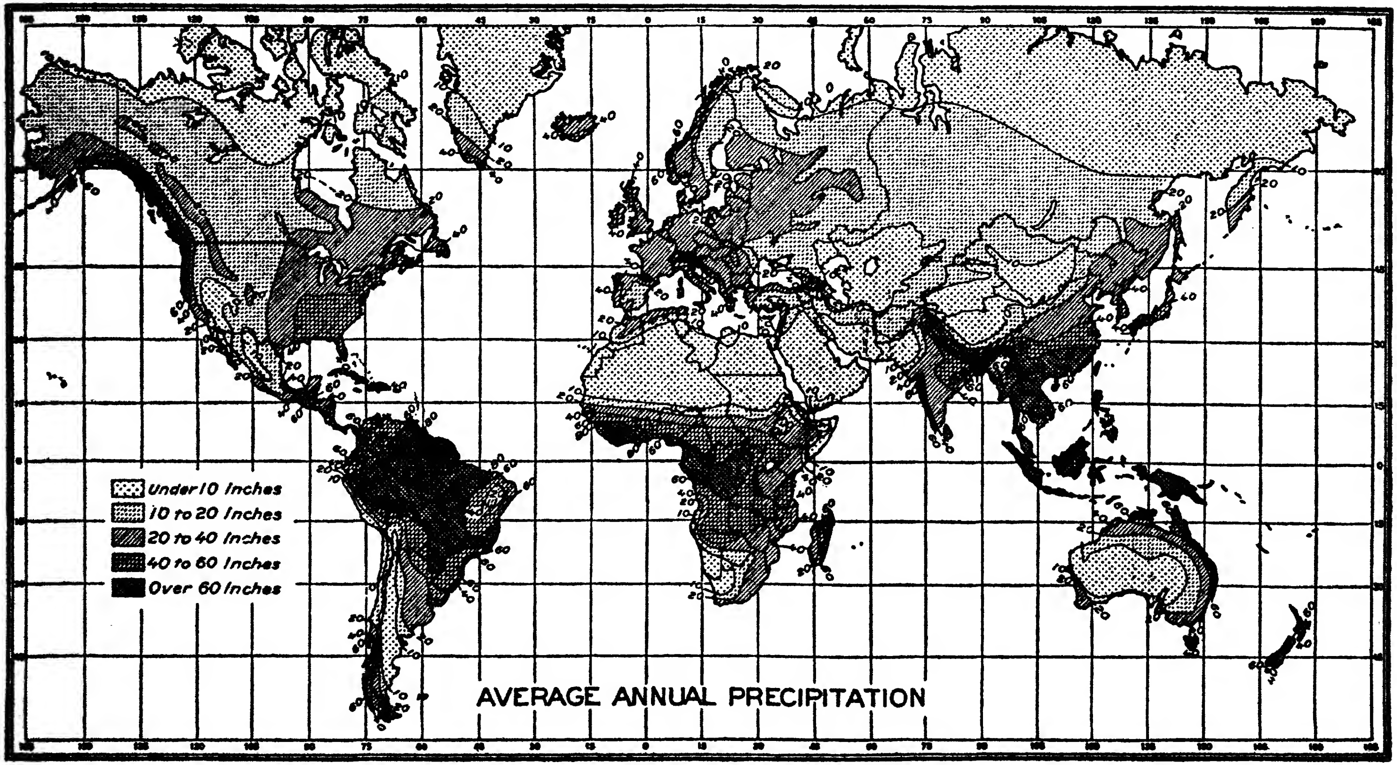


FIG. 21. Average annual precipitation of the world in inches. (After Henry *et al.*)

They are designated by their German name, graupel, and correspond to soft hail.

Sleet means precipitation in the form of small particles of clear ice. It is formed by raindrops falling through layers of cold air. In popular terminology a mixture of rain and snow or partly melted snow is also referred to as sleet.

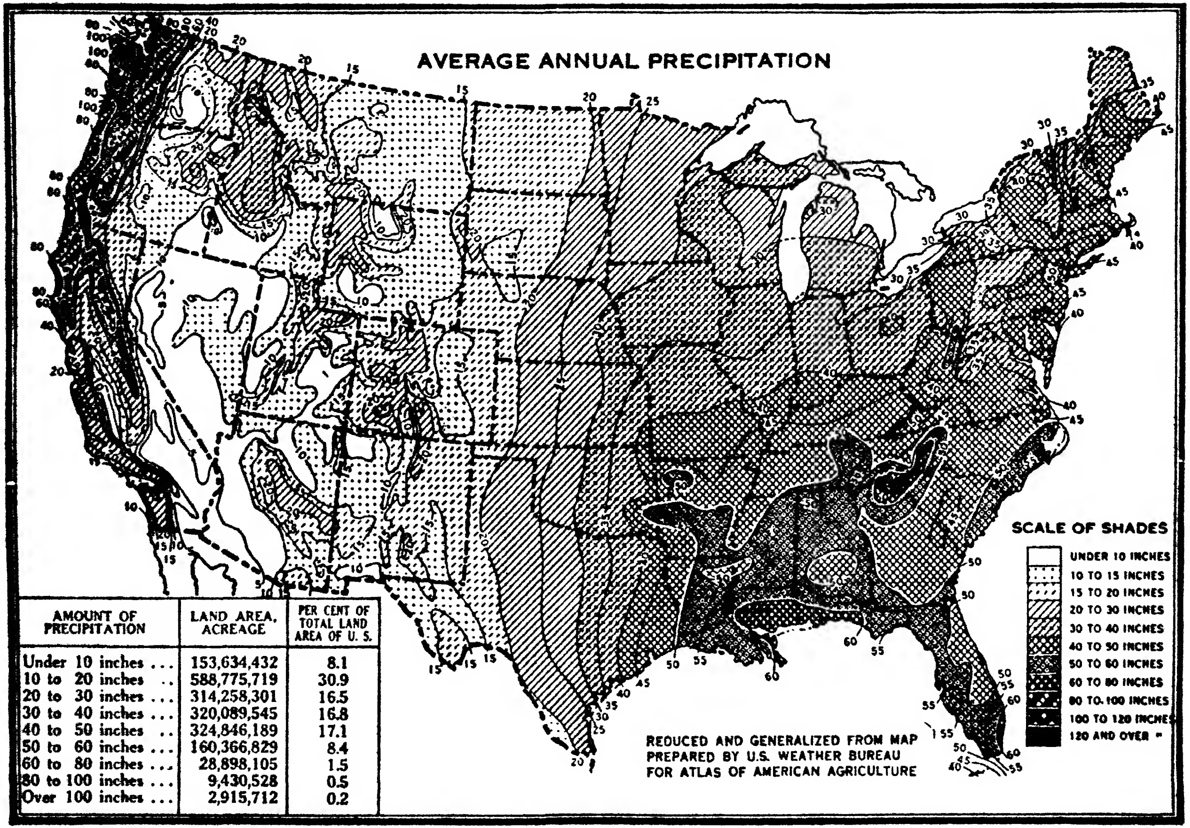
Glaze, popularly called an ice storm, is caused by ice forming on the surface of the soil or over vegetation from the freezing of rain as it strikes. Considerable damage is at times caused to upright vegetation by the accumulated weight of the ice so formed. If the ice layer remains long enough, winter wheat or other winter annual plants may be damaged by suffocation.

Measurement of precipitation. The ordinary rain gauge as used by the United States Weather Bureau consists of a galvanized iron cylindrical can, 8 inches in diameter, the mouth of which is circular, beveled on the outside to form a sharp edge. The receiver is funnel-shaped; the orifice leading from the funnel discharges into a brass cylinder, 20 inches in depth, the inside area of which is exactly one-tenth of the area of the receiver rim. The water caught is measured by a wooden scale and recorded in hundredths of an inch. Precipitation in the form of snow and ice is melted and recorded as water. Various types of recording gauges are also available. Such equipment is valuable for rainfall intensity studies.

Annual precipitation. The normal annual rainfall over the surface of the globe is subject to wide variations, ranging from less than 8 inches in certain desert areas to more than 400 inches as at Cherra Punji, India, where a rainfall of 428 inches per annum has been recorded. Figure 21, taken from Henry *et al.* (8), shows in a generalized way the world distribution of annual precipitation.

The older classifications of climates were based strictly on amounts of annual precipitation received in different regions. The humidity provinces thus established are presented in Table 4, together with the approximate percentage of the land area of the world covered by each (Smith, 17).

Figure 22, taken from Baker (1), shows the average annual precipitation over the United States, together with the land area and the percentage distribution of each frequency class.



AMOUNT OF PRECIPITATION	LAND AREA, ACREAGE	PER CENT OF TOTAL LAND AREA OF U. S.
Under 10 inches ...	153,634,432	8.1
10 to 20 inches ..	588,775,719	30.9
20 to 30 inches ...	314,258,301	16.5
30 to 40 inches ...	320,089,545	16.8
40 to 50 inches ..	324,846,189	17.1
50 to 60 inches ...	160,366,829	8.4
60 to 80 inches ...	28,898,105	1.5
80 to 100 inches ...	9,430,528	0.5
Over 100 inches ...	2,915,712	0.2

FIG. 22. Average annual precipitation of the United States in inches. (After Baker.)

TABLE 4. DISTRIBUTION OF PRECIPITATION OVER THE LAND AREA OF THE WORLD TOGETHER WITH THE CLIMATIC CLASSIFICATION AND THE PERCENTAGE IN EACH AREA.

Annual Precipitation, in Inches	*Climatic Classification*	*Percentage of Land Area*
Less than 10	Arid	25.0
10–20	Semiarid	30.0
20–40	Subhumid	20.0
40–60	Humid	11.0
60–80	Wet	9.0
80–120	Wet	4.0
120–160	Wet	0.5
Above 160	Wet	0.5

Seasonal Distribution of Precipitation. The seasonal distribution of precipitation is directly associated with the effective use of moisture by plants, adaptation of crop plants, and the agricultural utilization of any given area. This factor is discussed in detail in Chapter XIII dealing with moisture efficiency and again in Chapter XX on the classification of climates.

LOSSES OF MOISTURE

Sources of Loss. Moisture falling on the surface of the earth may either enter the soil, run off the surface, or be lost by direct evaporation. The amount that runs off is of no benefit to plants, but may cause severe damage through erosion. Of the moisture entering the soil, some may percolate to a depth beyond reach of the roots of plants and be thus lost in the drainage water, or it may be dissipated into the air by direct evaporation or by means of transpiration through plants.

Runoff. The amount of moisture lost by runoff is determined by a great variety of factors such as intensity of rainfall, topographical features, vegetative cover, and condition of the soil. Soil conditions influencing runoff are: texture; type; mechanical condition, especially of the surface, as to structure, amount of water present, and the form in which the water is held (that is, whether in the liquid or solid phase); and temperature. The amount and form of organic matter in the soil greatly influence its structure and ability to take on and hold moisture.

The influence of topographical features on runoff is self-evident. The effects of rainfall intensities will be briefly dealt with.

Rainfall Intensity. The term "rainfall intensity" refers to the receipts of precipitation at given time intervals. Yarnell (21) presents rainfall intensity-frequency data for the various areas of the United States. Charts prepared by Yarnell show the maximum precipitations in periods of five minutes to two hours that may be expected to occur with average frequencies in from 2 to 100 years. The numerous charts presented by Yarnell and maps given by Kincer (11) show material differences in rainfall intensities in the various portions of the United States. The highest intensities occur along the Gulf and along the South Atlantic coast. Relatively high intensities are also found in the Great Plains and especially in the southern Great Plains area. The intensities in the Corn Belt states are significantly lower than in the Cotton Belt. The lowest intensities are found in the Pacific Northwest. The direct relationship of precipitation-intensity data to crop production and erosion control problems is evident. Unfortunately the intensity is highest in those areas of the United States where a high percentage of the crop land is planted to intertilled crops such as cotton, sorghums, and corn. This adds materially to the problem of controlling soil erosion losses.

Evaporation. The loss of moisture through evaporation in relation to the receipt of precipitation is of great agricultural importance and will be dealt with in detail under the heading of moisture efficiency. It becomes a problem of special significance in those agricultural areas bordering upon the minimal thresholds of crop production.

According to Kincer, "the rate of evaporation of moisture from the soil depends principally upon the amount of moisture present, the soil texture, the temperature, wind movement, and relative humidity of the atmosphere."

Briggs and Belz (3) show the intimate relationship between rainfall and evaporation in its application to crop production by constructing lines of equal and equivalent rainfall for the states of the Great Plains area. Their outline map is reproduced as Fig. 23. Near the Canadian border the lines of equal and equivalent rainfalls for 20 and 15 inches per annum coincide. It will be observed, however, that they become separated by increasing distances in

passing to the south, owing to increases in rates of evaporation. It is necessary to move more and more to the eastward from the lines representing the actual 20- and 15-inch isohythes, lines of equal rainfall, in order to find conditions that are equally favorable for crop production so far as rainfall is concerned, that is, to enter the so-called equivalent rainfall region.

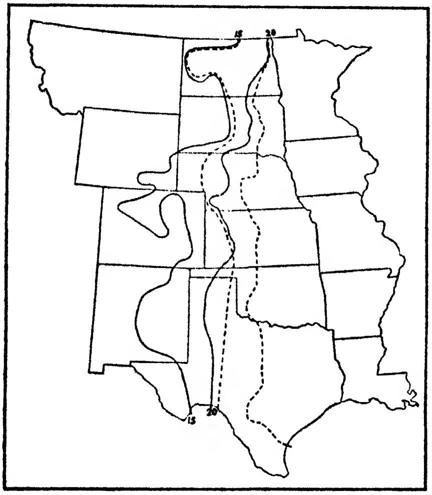


Fig. 23. Outline map of the states of the Great Plains area, showing lines of equal and equivalent rainfall. The solid lines marked 15 and 20 pass through points of equal annual rainfall; the corresponding dotted lines pass through points having rainfalls equivalent to 15 and 20 inches, respectively, on the Canadian boundary. (After Briggs and Belz.)

Exacting data of rates of evaporation from free water surfaces are limited. The rates are variable but depend primarily on the temperature, relative humidity, and wind velocity. Thompson (19) reports an annual evaporation of 87.64 inches, that is, five times the annual rainfall, from Kimberley, South Africa. Livingston (14) gives the rainfall evaporation ratios for 112 stations in the United States. This ratio refers to the quotient of the division of the total rainfall for the average frostless season by the total evaporation from a water surface during that period. The values vary from 0.04 for Winnemucca, Nevada, to 1.76 for Hatteras, North Carolina, and to the extremely high ratio of 3.84 for Tatoosh Island, Washington.

Mead (15) brings out that while evaporation from a free water surface is subject to variations from year to year it is less variable than precipitation.

Measurement of Evaporation. Any measurement of evaporation is an approximation of the actual loss of water that takes place through this source. Various types of evaporimeters have been used. The most common type of evaporation pan used in the United States is described by Kadel (10). In Europe the Piche

atmometer is extensively used for purposes of evaluating the capacity of the air to take up moisture. In this instrument a disk of filter paper withdraws water from a graduated glass reservoir.

Livingston's porous porcelain cup atmometers are widely used, especially in connection with transpiration experiments. Water evaporates from the unglazed portions of these atmometer cups which are connected by means of a glass tube to a water reservoir.

Transpiration. Transpiration, the taking up of water from the soil by plants and dispersing it into the atmosphere, is one of the most important sources of losses of soil moisture. Transpiration has been referred to as a necessary evil. This may be so, but it is also necessary to keep in mind that transpiration is a vital function; without it, since it is so closely related to photosynthesis, growth is impossible.

REFERENCES

1. Baker, O. E., "A graphic summary of American agriculture," *U. S. Dept. Agr. Yearbook* 1921, 407–506.
2. Blair, T. A., *Weather Elements*. Prentice-Hall, New York, 1937.
3. Briggs, L. J., and J. O. Belz, "Dry farming in relation to rainfall and evaporation," *U. S. Dept. Agr., Bur. of Plant Industry, Bull.* 188, 1910.
4. Dungan, G. H., "Effect of hail injury on the development of the corn plant," *Jour. Amer. Soc. Agron.*, 20:51–54 (1928).
5. Eldredge, J. C., "The effect of injury in imitation of hail damage on the development of small grain," *Iowa Agr. Exp. Sta. Res. Bull.* 219, 1937.
6. Garber, R. S., and M. M. Hoover, "Influence of corn smut and hail damage on the yield of certain first generation hybrids between synthetic varieties," *Jour. Amer. Soc. Agron.*, 27:38–45 (1935).
7. Hann, J., *Handbook of Climatology*, trans. German by R. DeCourcy Ward, Part I, "General Climatology," Macmillan, New York, 1903.
8. Henry, A. J., J. B. Kincer, H. C. Frankenfield, W. B. Gregg, B. B. Smith, and E. N. Munns, "Weather and Agriculture," *U. S. Dept. Agr. Yearbook* 1924:457–558.
9. Hume, A. N., and C. Franzke, "The effect of certain injuries to leaves of corn plants upon weights of grain produced," *Jour. Amer. Soc. Agron.*, 21:1156–1164 (1929).
10. Kadel, B. C., "Instructions for the installation and operation of class 'A' evaporation stations," *U. S. Dept. Agr., Weather Bur. Cir. L.* Instrument Division, 1919.

11. Kincer, J. B., *Atlas of American Agriculture*, Part II, Sec. A., "Precipitation and humidity." Govt. Print. Office, Washington, 1922.
12. Klages, K. H. W., "The effects of simulated hail injuries on flax," *Jour. Amer. Soc. Agron.*, 25:534–540 (1933).
13. Köppen, W., "Klassification der Klimate nach Temperatur, Niederschlag und Jahreslauf," *Petermann's Mitteilungen*, 64:193–203, and 243–248 (1918).
14. Livingston, B. E., "A single index to represent both moisture and temperature conditions as related to plants," *Physiol. Res.*, 1:421–440 (1916).
15. Mead, D. W., *Hydrology*. McGraw-Hill, New York, 1919.
16. Schander, R., "Über Hagelbeschädigungen an Roggen, Weizen und Hafer," Fühlings *Landw. Zeit.*, 63:657–703 (1914).
17. Smith, J. W., *Agricultural Meteorology*. Macmillan, New York, 1920.
18. Taylor, G., "The frontiers of settlement in Australia," *Geog. Rev.*, 16: 1–25 (1926).
19. Thompson, W. R., *Moisture and Farming in South Africa*. Central News Agency, South Africa, 1936.
20. Ward, R. D., *The Climates of the United States*. Ginn, Boston, 1925.
21. Yarnell, D. L., "Rainfall intensity — frequency data," *U. S. Dept. Agr. Misc. Pub.* 204, 1935.

Chapter XIII

HUMIDITY PROVINCES

Efficiency of Precipitation. The effectiveness of a given amount of annual precipitation is not the same in different regions with varying climatic conditions. The influence of rates of evaporation on efficiency of precipitation was alluded to in the previous chapter. It, together with the seasonal distribution of the precipitation in relation to the requirements of crops grown, constitutes the main factor determining the effectiveness of a given amount of precipitation.

Numerous efforts have been made to improve upon the establishment of humidity provinces based strictly on receipts of annual precipitation. The main objections to this older system of designating such humidity provinces, with a total disregard of possible losses of the moisture received, are obvious. The most refined and useful method of establishing humidity provinces would be to determine available moisture in the soil during the course of the growing season in relation to the special requirements of the predominating crops grown. This would require a tremendous amount of detailed work. Since such data are not available, more expedient criteria of the utilization of moisture receipts must of necessity be resorted to even though they may not take into consideration all possible losses of moisture. None of the methods for determining the efficiency of precipitation takes into consideration the losses due to runoff and percolation. The fact remains that the establishment of humidity provinces must be based on the particular climatological data that are available over large territories so that the classification setup may be extensively applied in comparat ve studies of the humidity factor in the various crop producing areas of the world.

Precipitation-evaporation ratio. Transeau (15) as early as 1905 suggested the use of both precipitation and evaporation data in an attempt to combine in a single number the influences of the

temperature and moisture factors of the environment in their effects on the distribution of forest trees in the eastern portion of the United States. Reasoning that evaporation depends upon the temperature of the evaporating surface, the relative humidity of the air, and the velocity of the wind, and that these same factors affect transpiration, he suggested an index of precipitation effectiveness by using the quotient of total annual precipitation and annual evaporation.

Penck (9) used precipitation and evaporation data in his classification of climates. He placed the boundary between the arid and humid provinces at the point where precipitation and evaporation were equal, or where the precipitation-evaporation ratio is unity.

Meyer's P-SD quotient. Since reliable evaporation data are not available from many stations, Meyer (8) recommended an evaporation substitute in setting up his "Niederschlag-Sättigungs-defizit" or precipitation-saturation deficit quotient, also referred to as the N–S ratio. The P–SD quotient is calculated by dividing the annual precipitation in millimeters by the absolute saturation deficit of the air expressed in millimeters of mercury. Jenny (5) gives the values of the P–SD quotients as well as the values of Lang's rain factor for 144 stations in the United States. Figure 24, taken from Jenny and based upon his calculations, gives the humidity provinces of the United States as indicated by P–SD ratios. Prescott (11) made use of the same ratio in his studies of moisture conditions in Australia.

Meyer recognizes that his P–SD ratio does not take account of wind velocity and atmospheric pressure in their effects on evaporation, or of such features as the distribution of rainfall, sunlight, fog, or temperature except insofar as these factors are reflected by the saturation deficit. His ratio has the advantage of relative simplicity. Szymkiewicz (12) recommends a very complex measure of evaluating the effectiveness of precipitation by dividing the amount of precipitation received by his index of evaporation. Since this index of evaporation is determined from an equation involving vapor pressure deficit, water vapor pressure, and atmospheric pressure as well as temperature, it can be calculated only for stations where complete meteorological records are available. The P–SD ratio can be determined for any station recording precipitation, temperature, and relative humidity. Furthermore,

evaporation may for practical purposes be regarded as a function of the saturation deficit.

Trumble (16) made use of "saturation deficiency and its relation to rainfall as expressed by the Meyer ratio" in studies of effective soil moisture in Australia.

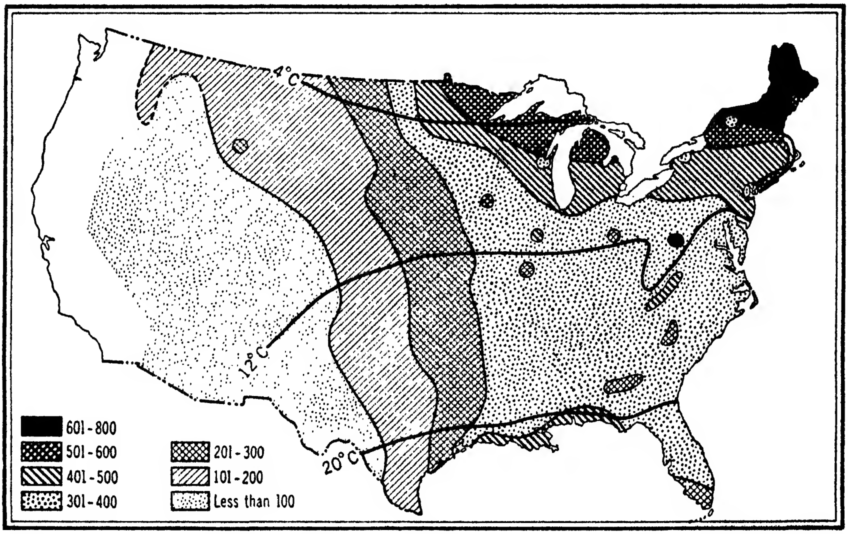


FIG. 24. Humidity provinces of the United States as determined by Meyer's P–SD quotient, and annual isotherms of 4, 12, and 20°C, or 39.2, 53.6, and 68°F. (After Jenny.)

Jenny states that the P–SD quotient "is a satisfactory substitute for Transeau's precipitation-evaporation ratio and has the advantage of international application."

The limits of the major humidity provinces based on the P–SD quotients are given in Table 5.

Lang's rain factor. Lang (7) used the rain factor in connection with his investigations of possible temperature and rainfall limits of soil zones. It is calculated by dividing the annual precipitation expressed in millimeters by the mean annual temperature in degrees centigrade. This index of precipitation efficiency is commonly referred to as the P–T ratio.

The climates of regions with rain factor values of from 10 to 40 are classified as arid, those with values of from 40 to 160 as humid, while those with values of more than 160 are designated as wet.

Jenny gives a map of the United States based on Lang's rain factor. This map is reproduced as Fig. 25. The rain factors were calculated for over 2,000 meteorological stations by using the data collected by the United States Weather Bureau (17). Hirth (4) published a map of the world showing the humidity provinces based on Lang's rain factor. Hirth points out that the isonotides, lines of equal rain factors, should not be regarded as lines but as

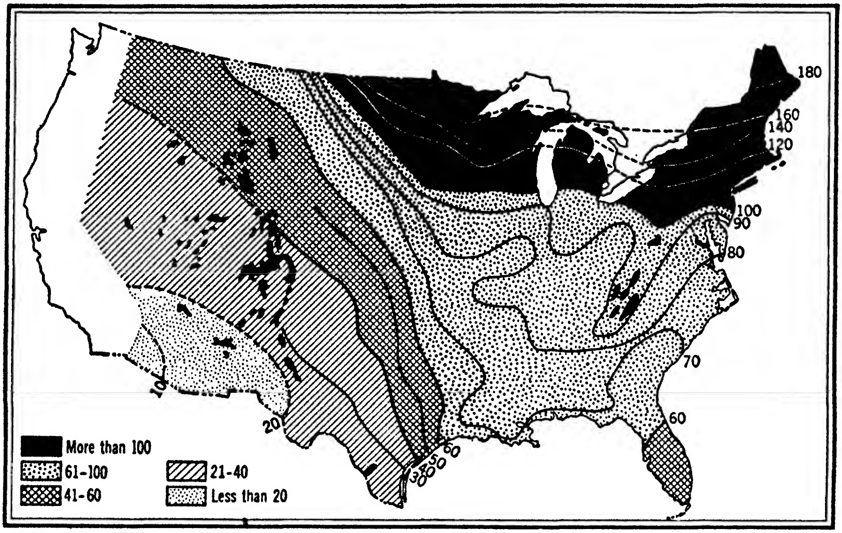


Fig. 25. Humidity provinces of the United States as determined by Lang's rain factor or the P–T ratio. (After Jenny.)

zones of varying breadths; that is, every designated humidity province is separated from the adjoining province by a transition zone.

A comparison of Figs. 24 and 25, that is, the humidity maps of the United States based on Meyer's P–SD and Lang's P–T quotients, respectively, brings out certain discrepancies between these two indices. On the basis of distribution of native vegetations and utilization of areas for crop production purposes the P–T quotients are entirely too high for the northern Great Plains area. It is evident that Meyer's P–SD ratios give a truer picture of existing humidity conditions than Lang's P–T quotients.

While temperature is one of the climatic factors influencing rates of evaporation, it must be recognized that other factors are definitely involved. Generally the saturation deficit provides a more reliable

index of the combined effect of all the factors involved in determining rates of evaporation than temperature.

Index of aridity. De Martonne's (2) index of aridity represents a slight modification of Lang's rain factor in that he suggests a division of the annual precipitation in millimeters by the mean annual temperature in degrees centigrade plus ten. The values of the index would consequently be lower than for the P–T quotients. Andrews and Maze (1) defined the monthly conditions of aridity in Australia by using De Martonne's index, by assuming a monthly index of 1 as a significant indication of a condition of aridity. Perrin (10) observes that the factor does not apply well to cool zones owing to the high values obtained during the cold months. De Martonne (3) presents a world map of the index of aridity.

The same objections made to the broad application of Lang's rain factor, P–T quotients, apply also to De Martonne's index of aridity, in that they are both based on temperature and assume evaporation to be a function of temperature.

Thornthwaite's precipitation effectiveness index. Thornthwaite (13 and 14) in his classification of the climates of North America and of the world expressed Transeau's precipitation-evaporation ratio in an empirical form so that the values obtained would correspond to the values of his temperature index. The formula for the precipitation effectiveness, P–E, index is given as:

$$\text{P–E index} = \sum_{n=1}^{12} 10 \left(\frac{P}{E}\right)n$$

In calculating this index it is necessary to obtain the P/E ratios of each of the 12 months of the year. These are multiplied by ten to avoid the inconvenience of dealing with fractions. The P–E index is then ten times the sum of the 12 monthly P/E ratios. In this respect it differs from Transeau's precipitation-evaporation ratio, which was based directly on the total annual precipitation and evaporation. Evaporation refers to the evaporation from a free water surface in inches.

Thornthwaite also presents a formula for calculating the precipitation-effectiveness index for stations for which evaporation data are not available by making use of the mean monthly tem-

perature and precipitation values. According to Thornthwaite, the values obtained by this formula correspond sufficiently close for practical purposes to the one based on evaporation data. The formula for the P–E index based on mean monthly precipitation in inches and temperatures in degrees Fahrenheit is presented below:

$$\text{P–E index} = \sum_{n=1}^{12} 115 \left(\frac{P}{T-10}\right)_n^{\frac{10}{9}}$$

Thornthwaite (13) states that the data used in the development of the above formula were most abundant in the temperature range between 40 and 80°F and did not extend below 30 or above 90°F. He recommends that temperatures below 28.4°F be calculated on the basis of the effectiveness at that temperature.

Table 5 gives the values of the limits of the P–E indices of the five major humidity provinces established by Thornthwaite and the characteristic vegetation of each province. For purposes of comparison the limits of the values of the P–SD quotients for each province as calculated by Prescott are also presented. Thornthwaite indicates that the P–E index of 48 approximately separates the humid east from the semiarid and arid west in the United States.

TABLE 5. THE LIMITS OF FIVE MAJOR HUMIDITY PROVINCES AND CHARACTERISTIC VEGETATIONS OF EACH PROVINCE BASED ON THORNTHWAITE'S PRECIPITATION EFFECTIVENESS (P–E) INDEX. FOR PURPOSES OF COMPARISON THE LIMITS OF MEYER'S P–SD QUOTIENTS AS CALCULATED BY PRESCOTT ARE ALSO GIVEN

Humidity Province	*Characteristic Vegetation*	*P–E Index*	*Calculated P–SD Quotient* *
A Wet	Rain forest	128 and above	277 and above
B Humid	Forest	64–127	177–277
C Subhumid	Grassland	32–63	89–177
D Semiarid	Steppe	16–31	44–89
E Arid	Desert	Less than 16	0–44

* Assuming E = 260 S.D.

Figure 26, reproduced from Thornthwaite's (13) map, gives the humidity provinces of the United States based on the P–E index.

Thornthwaite also takes into consideration the seasonal distribution of precipitation effectiveness in his classification of climates.

Four subtypes are recognized: "r," designating abundance of moisture at all seasons; "s," moisture deficient in summer; "w," moisture deficient in winter; and "d," moisture deficient at all seasons.

The P–E index can be used to good advantage in crop distribution studies, especially when used in connection with Thornthwaite's classification of climates. When possible the index should

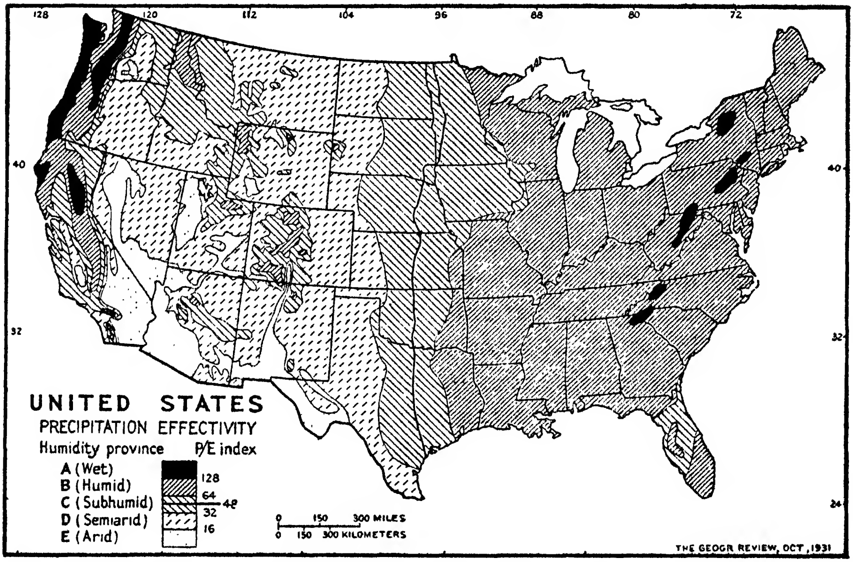


FIG. 26. Humidity provinces of the United States based on the precipitation effectiveness (P–E) index. (After Thornthwaite.)

be based on evaporation rather than on monthly temperatures. When the P–E index is based on temperatures it becomes subject to the criticisms pointed out in connection with the application of Lang's P–T quotients.

Köppen's Designation of Boundaries between Dry and More Humid Areas. Köppen (6) in his classification of climates assumes evaporation to be a function of temperature. The critical division between his dry, the B, and more humid, C and D, climates is arbitrarily placed at the point where the annual precipitation and evaporation are in equilibrium. In this he does not, however, make use of direct evaporation data, but evaluates them on the basis of mean annual temperature plus a variable factor. Köppen introduced the novel idea of greater efficiency of precipitation in

areas of winter than in areas of summer precipitation by assuming that a higher percentage of the moisture is lost by direct evaporation in summer than in winter. The efficiency is placed at the neutral point in areas of moderate temperatures with rainfall rather evenly distributed throughout the year. In areas of summer rainfall the variable factor is increased by 30 per cent to give a corresponding efficiency. Likewise 30 per cent is taken from the variable factor in regions of winter precipitation. In other words, the annual amount of precipitation required to place an area in the more humid province need not be so great in areas of winter precipitation as in areas with rather uniform or with summer precipitation. The equilibrium at the outer boundary of the steppe regions is then stated by:

$$P = t + y$$

P, expressed in centimeters, refers to the amount of the critical annual precipitation; t is the annual mean temperature in degrees centigrade; and y, the variable factor, can have three different values, 22, 33, or 44, in accordance with the seasonal distribution of precipitation for the area in question. The value of y at the neutral point, that is, for areas with fairly uniform precipitation, is placed at 33; with summer rainfall at 44; and with precipitation concentrated in the winter months at 22.

Köppen illustrates the application of the above by using the annual mean moisture and temperature data for Seville, Spain, $P = 47$, $t = 20$. Assuming that the annual precipitation was uniformly distributed throughout the year, then the boundary of the steppe climate would be at $20 + 33 = 53$, which would place Seville in the dry, B, climate. It would fall within the boundary of the steppe since the annual precipitation P is less than $t + y$. Since, however, Seville is located in an area of winter precipitation, the boundary of the steppe climate is placed at $20 + 22 = 42$, that is, the climate classifies as C though close to the boundary of the dryer B climates. With the introduced value of y for areas of winter rains the amplitude of the $t + y$ becomes less than that of P.

Areas having less than the critical amounts of precipitation are designated as steppes while those with less than half the critical amounts are deserts.

Table 6, taken from Köppen, shows the outer boundaries of the desert and steppe areas in relation to prevailing mean annual

temperatures. The values given by him are for the neutral point only. The corresponding values for regions with a summer and winter concentration of moisture were calculated by the formula $P = t + y$. The boundaries of the desert and steppe are determined by a combination of precipitation, temperature, and seasonal distribution of precipitation. It will be observed that the desert boundary is in every case half that of the steppe, also that Köppen did not consider the formula of the equilibrium of precipitation to temperature plus y as an exact mathematical value.

TABLE 6. THE OUTER BOUNDARIES OF DESERT AND STEPPE AREAS IN RELATION TO PREVAILING MEAN ANNUAL TEMPERATURES ACCORDING TO KÖPPEN

Mean Annual Temperatures in Degrees Centigrade	*25*	*25–20*	*20–15*	*15–10*	*10–5*	*5*
Neutral zone — uniform distribution of precipitation — y = 33						
Outer boundary of steppe (cm) . . .	64	58	52	46	40	32
Outer boundary of desert (cm) . . .	32	29	26	23	20	16
Precipitation concentrated in summer months — y = 44						
Outer boundary of steppe (cm) . . .	75	69	63	57	51	43
Outer boundary of desert (cm) . . .	37.5	34.5	31.5	28.5	25.5	21.5
Precipitation concentrated in winter months — y = 22						
Outer boundary of steppe (cm) . . .	53	47	41	35	29	21
Outer boundary of desert (cm) . . .	26.5	23.5	20.5	17.5	14.5	10.5

Van Royen (18) points out some of the limitations of applying Köppen's formula to conditions met with in North America. He not only expresses the main criticism to the employment of a formula based on temperature, even with the modifications introduced by Köppen, but also gives the present limitations to be recognized in basing an index of precipitation effectiveness strictly upon evaporation data.

Vegetation as an Index of Moisture Conditions. Any vegetation must, in order to survive, establish an equilibrium with the environmental factors under which it develops. Since the availability of water is one of the most important factors of the environment, it is evident that the relative development of native as well as introduced species provides a direct index of existing moisture conditions. Plants provide an index of existing moisture conditions both by means of the species represented and by the relative amount

of growth or luxuriance of individual species or groups of species. Furthermore, the response of plants is directly related not only to the existing climatic but also to the edaphic factors of the environment. In this respect the existing plant cover provides a more reliable and comprehensive index of moisture conditions than any possible mathematical formulation of precipitation and evaporation data. This does not mean that it is of no value to establish humidity provinces based on the climatic factors involved in the efficient use of water by plants. It simply means that the responses of plants provide the best possible index of existing moisture conditions. However, it must be recognized in this connection that the evaluation of plant responses demands a great deal of experimental work. Such data are now available for only limited areas, and even where available they are not comparable. Consequently, for the time being, the ecologist must be satisfied with the delineation of humidity provinces based on meteorological elements. It is quite evident from the discussion presented in this chapter that humidity provinces based on both precipitation and evaporation data provide a far better index of existing moisture conditions than the establishment of such provinces based on moisture receipts alone.

REFERENCES

1. Andrews, J., and W. H. Maze, *Proc. Linn. Soc., N. S. W.*, 58:105 (1933).
2. De Martonne, E., Aréisme et indice d'aridité, *Comptes Rendus de l'Acad. des Sci. (de Paris)*, 182:1395–1398 (1926).
3. ———, "Regions of interior drainage," *Geog. Rev.*, 17:397–414 (1927).
4. Hirth, P., "Die Isonotiden," *Petermann's Mitt.* 72:145–149 (1926). Reviewed in *Geog. Rev.*, 17:335–338 (1927).
5. Jenny, H., "A study on the influence of climate upon the nitrogen and organic matter content of the soil," *Mo. Agr. Exp. Sta. Res. Bull.* 152, 1930.
6. Köppen, W., *Die Klimate der Erde.* Walter De Gruyter & Co., Berlin, 1923.
7. Lang, R., *Verwitterung und Bodenbildung als Einführung in die Bodenkunde.* Schweizerbart 'sche Verlagsbuchhdlg, Stuttgart, 1920.
8. Meyer, A., "Über einige Zuzammenhänge Zwischen Klima und Boden in Europa," *Chemie der Erde*, 2:209–347 (1926).

9. Penck, A., "Versuch einer Klimaklassifikation auf physiographischer Grundlage," *Sitz. Ber. phys. math. Kl. Preuss. Akad. Wiss.*, Berlin, 1910, p. 236.
10. Perrin, H., *Comptes Rendus de l'Acad. des Sci.* (*de Paris*), 192:1271 (1931).
11. Prescott, J. A., "Single value climatic factors," *Trans. Roy. Soc. So. Australia*, 58:48–61 (1934).
12. Szymkiewicz, D., "Études climatologiques," *Acta Societatis Botanicorum Poloniae*, 2:130 and 239 (1925).
13. Thornthwaite, C. W., "The climates of North America according to a new classification," *Geog. Rev.*, 21:633–655 (1931).
14. ———, "The climates of the earth," *Geog. Rev.*, 23:433–440 (1933).
15. Transeau, E. N., "Forest centers of eastern America," *Amer. Nat.*, 39: 875–889 (1905).
16. Trumble, H. C., "The climatic control of agriculture in South Australia," *Trans. Roy. Soc. So. Australia*, 61:41–62 (1937).
17. *U. S. Dept. Agr. Weather Bureau, Bull. W. Ed.* 2, 1926.
18. Van Royen, W., "The climatic regions of North America," *Mo. Wea. Rev.*, 55:315–319 (1927).

Chapter XIV

THE USE OF WATER BY PLANTS

The Efficiency of Transpiration. The relationship between the units of water transpired by a plant and the equivalent units of dry matter produced is expressed in a variety of fashions. The terms commonly used are the transpiration ratio, the transpiration coefficient, and water requirement. Since a ratio is definitely involved, the term "transpiration ratio" is quite appropriate. The transpiration ratio refers to the ratio between the amount of dry matter accumulated by a plant, exclusive of the roots, to the amount of water transpired for a given interval of time; in the case of annual plants this period is, unless otherwise stated, from emergence to maturity. Only in the case of root crops is the weight of underground portions of plants included in the calculations of the ratios. Thus if a plant producing 4 grams of dry matter transpired 2,000 grams of water during its course of development, the transpiration ratio would be 1:500. This figure is, according to the definition presented by Briggs and Shantz (3), subject to a minor correction for the amount of water remaining in the plant at maturity.

It is to be noted that the transpiration ratio depends on both the amount of dry matter produced and the amount of water transpired. It is important to keep this in mind. Any factor of the environment affecting the growth processes of the plant becomes directly effective in determining the transpiration ratio to the extent to which it influences the amount of dry matter assimilated.

The term "transpiration coefficient" has the advantage over the term "transpiration ratio" that it obviates the necessity of stating the figure obtained in the form of a ratio.

The term "water requirement" should not be confused with the water utilization of plants growing under field conditions. In controlled water-requirement or transpiration-ratio experiments losses of soil moisture other than through the leaves and stems of plants are prevented by the experimental methods used. This

is decidedly not the case when plants are grown under field conditions. Thus when Hughes and Henson (7) define the term "water requirement" as "the pounds or units of water required to produce a pound or unit of dry matter" it must be kept in mind that such a definition applies only to the results obtained in controlled experiments and not to actual field conditions.

Maximov (12) uses the term "efficiency of transpiration," referring to the amount of dry matter accumulated by plants for each 1,000 parts of water transpired, using equivalent units. Thus if the transpiration coefficient is 400 the efficiency of transpiration becomes 1,000/400 or 2.5.

The Transpiration Coefficients of Various Crop and Weed Plants. The most extensive investigations dealing with the comparative transpiration ratios of plants in this country are reported by Briggs and Shantz (1, 2, 3), Shantz and Piemeisel (16), and by Dillman (5). Table 7 gives the transpiration coefficients and efficiencies of transpiration of important crop plants and weeds compiled from the data presented by Shantz and Piemeisel from experiments conducted at Akron, Colorado, and by Dillman from tests at Newell, South Dakota, and Mandan, North Dakota.

Figure 27 gives a graphical presentation of the transpiration coefficients of important crop plants at Akron for the years 1911–1917, inclusive, in relation to the evaporation from a free water surface for each year at that station.

The experimental methods employed by Shantz and Piemeisel and by Dillman were essentially the same; it is therefore possible to make direct comparisons between the results reported. The plants were grown inside a screened enclosure, which reduced the solar radiation to about 80 per cent of its normal value. Control experiments with freely exposed plants showed that the enclosure reduced the transpiration coefficients about 22 per cent.

The figures reported by Shantz and Piemeisel from Akron and by Dillman for the northern Great Plains area stand in close agreement as far as the relative values for the different crops tested are concerned. It will be observed, however, that the transpiration coefficients reported by Dillman are in all instances lower than those given by Shantz and Piemeisel. This is to be expected in view of the lower temperatures and lower rates of evaporation at Newell and Mandan as compared with those prevailing at Akron. The

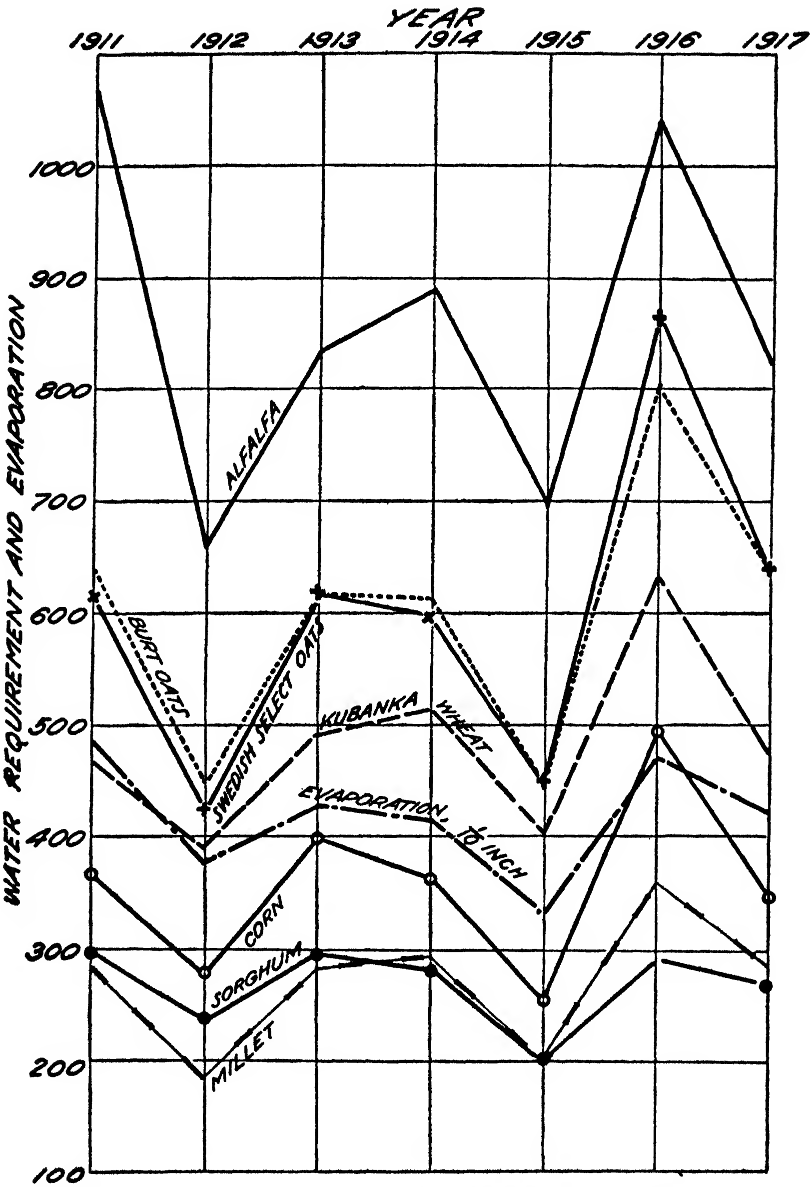


FIG. 27. The transpiration coefficients of different crops and evaporation in tenths of an inch at Akron, Colorado, for the years 1911–1917. (After Shantz and Piemeisel.)

April to September, inclusive, evaporation at Akron was 42.11 inches as compared to 32.56 inches at Newell.

TABLE 7. THE TRANSPIRATION COEFFICIENTS AND EFFICIENCIES OF TRANSPIRATION OF IMPORTANT CROP AND WEED PLANTS, COMPILED FROM THE RESULTS REPORTED BY SHANTZ AND PIEMEISEL FROM AKRON, COLORADO, AND FROM DILLMAN FOR THE NORTHERN GREAT PLAINS AREA

Plants	*Shantz and Piemeisel*		*Dillman*	
	Trans. Coeff.	Efficiency	Trans. Coeff.	Efficiency
Millet (Chaetochloa italica)				
Kursk	274	3.65	251	3.98
Sorghum (Andropogon sorghum)				
Dakota Amber Sorgo	285	3.51	268	3.73
Red Amber Sorgo	287	3.48	253	3.95
Sudan Grass	380	2.63	335	2.99
Corn (Zea mays)				
Northwestern Dent	361	2.77	—	—
Sugar Beet (Beta vulgaris)	377	2.65	304	3.29
Irish Cobbler Potato (Solanum tuberosum)	499	2.00	—	—
Turkey Wheat (Triticum vulgare)	455	2.20	—	—
Marquis Wheat (Triticum vulgare)	550	1.82	403	2.48
Kubanka Wheat (Triticum durum)	491	2.04	430	2.33
Hannchen Barley (Hordeum distichon)	523	1.91	—	—
Swedish Select Oats (Avena sativa)	604	1.66	536	1.87
Vern Rye (Secale cereale)	634	1.58	—	—
Flax (Linum usitatissimum)				
North Dakota Resistant No. 114	752	1.33	618	1.62
Brome Grass (Bromus inermis)	977	1.02	784	1.28
Grimm Alfalfa (Medicago sativa)	835	1.20	795	1.26
Sweet Clover (Melilotus alba)	731	1.37	—	—
Red Clover (Trifolium pratense)	759	1.32	—	—
Soybeans (Soja max)	646	1.55	—	—
Navy Beans (Phaseolus vulgaris)	656	1.52	—	—
Field Peas (Pisum sativum)	745	1.34	—	—
Buckwheat (Fagopyrum vulgare)	540	1.85	—	—
Russian Thistle (Salsola pestifer)	314	3.18	224	4.46
Pigweed (Amaranthus retroflexus)	305	3.28	261	3.83
Lambs Quarter (Chenopodium album)	658	1.52	435	2.30

The millets, sorghums, and corn are the most efficient of the crop plants in the utilization of water. The small grains require almost twice as much water, while the legumes use almost three times as much.

FACTORS INFLUENCING THE EFFICIENCY OF TRANSPIRATION

Introductory Statement. Generally those particular environmental conditions or factors favoring a healthy growth of plants also make for efficiency in the use of water. Efficiency in the use of water is in part determined by inherent plant characters but more directly by climatic and edaphic factors. The effective climatic factors were discussed in connection with the topic of humidity provinces and their establishment, Chapter XIII. The soil factors influence the transpiration ratio in relation to the extent to which they favor plant development. The plant characteristics correlated with the utilization of water and specific requirements for moisture were discussed in Chapter XI.

Kiesselbach (8) presents an outline of factors influencing transpiration, after which is patterned the outline given below.

A. *Climatic*

1. Temperature
2. Saturation deficit
3. Wind velocity
4. Light
5. Radiant heat
6. Air pressure
7. Evaporation from a free water surface

B. *Edaphic*

1. Nonnutrient salts
2. Soil fertility
3. Cropping system
4. Available moisture
5. Soil type
6. Soil texture
7. Soil temperature

C. *Plant Characters*

1. Root development
2. Leaf area
3. Ratio of absorbing to transpiring surface
4. Chlorophyll content of leaves
5. Diseases and presence of insects
6. Course of development
7. Structure of plant and especially of the leaves
8. Surface modifications of leaves
9. Osmotic pressure
10. Ability to withstand drought

In relation to the influence of the above factors on transpiration it may be stated, as was done by Kiesselbach, that some of them "are very profound in their effect, while others are comparatively insignificant."

Climatic Factors. The transpiration coefficient of plants is especially associated with factors influencing rates of evaporation. This is well brought out in Fig. 27. The close relationship between evaporation and the transpiration coefficients is very evident. As the evaporation index increases the efficiency of transpiration definitely decreases. This is of special importance to the water

economy of plants. The need for water is greatest during seasons with high temperatures, low humidity, and generally for those conditions favoring great losses of water not only from the crop plants but also from the soil through evaporation.

The transpiration coefficients of crop plants show material variations from season to season. Dillman gives an interesting illustration in the variations of the actual values of the transpiration coefficients of several crops grown during an 11-year period.

The ranges were as follows:

Alfalfa from 602 ± 5 in 1915 to 1,036 ± 14 in 1914
Kubanka wheat from 333 ± 2 in 1915 to 531 ± 8 in 1921
Sudan grass from 272 ± 2 in 1915 to 347 ± 4 in 1919
Millet from 177 ± 1 in 1915 to 316 ± 2 in 1913
Sorgo from 210 ± 4 in 1915 to 284 ± 3 in 1918

In connection with the above figures it is well to point out that the season of 1915 had the lowest evaporation index for the 11 years of the experiment, namely, 77 as compared to the average of 100.

Special attention must be given to the effects of humidity of the air in relationship to transpiration efficiency. Thus Kiesselbach reports a transpiration ratio of 1:340 for corn plants grown in a dry as compared to a ratio of 1:191 for plants grown in a humid greenhouse. Generally, it is to be expected that the transpiration coefficients for dry areas and climates run materially higher than for humid areas and climates. This point is substantiated by the coefficients of transpiration reported upon by investigators in different climatic areas. Thus Lawes and Gilbert report a coefficient of 225 for wheat in England as compared to coefficients of 359 by Hillriegel in Germany, 513 by Briggs and Shantz at Akron, Colorado, and 1,006 by Widtsoe in Utah. While these values may not be directly comparable owing to differences in the experimental methods used, they give valid indications of the greater requirement for moisture in semiarid and arid regions. This is a vital point to be taken into consideration in the agricultural utilization of dry areas.

Edaphic Factors. As with the climatic factors of the environment so also with the edaphic factors. Those particular soil conditions favoring a healthy and well-balanced growth of plants also favor an economic utilization of water. Generally variations in soil

factors do not produce the outstanding differences called forth by variations in climatic factors.

The amount of moisture in a soil available to plants at any given time may be a function of several conditions such as the amount of precipitation received, the time interval since the last effective rain, the method of handling the soil, conditions favoring penetration and percolation of moisture, and the sequence of cropping. In controlled experiments, that is, when the moisture content of the soil is held at definite levels, the highest efficiency in the use of moisture may be expected near or slightly lower than the level required for optimum growth. Kiesselbach and Montgomery (9) report transpiration coefficients of 290, 262, 239, 229, and 252 for corn grown in containers with moisture contents of 38, 31, 23, 17, and 13.5 per cent, respectively. Extremely high soil moisture contents interfere with normal growth; this accounts for the high coefficients at the higher moisture levels. The lower efficiency of transpiration of plants grown on soils with a high moisture content has been referred to by some investigators as being more or less caused by an induced extravagance in the use of water by plants grown under such conditions (Pfeiffer *et al.*, 13). Lack of available nutrients, especially lack of nitrogen resulting from the surplus of water in the soil, has been pointed out by Kiesselbach as a factor of importance. Should the water level of the soil become so high as to interfere with root development of plants, the transpiration ratio would be automatically increased on account of the lower efficiency of the plant in assimilation. On the other hand, should the moisture content of the soil be reduced to the point of inducing wilting, the efficiency of transpiration will be markedly reduced. This was the cause of the higher transpiration coefficient in the corn plants grown in the containers with only 13.5 per cent of moisture.

The direct effects of varying degrees of fertility of soils on the transpiration coefficient of corn is shown in Table 8, taken from Kiesselbach, giving the average results obtained in his experiments of 1911 and 1914. Variations in the transpiration coefficients of plants grown on different soil types are due more to variations in the plant nutrients of such soils than to differences in type or texture. It will be observed from Table 8 that the transpiration coefficients varied directly with the six degrees of soil fertility and the dry matter

produced. The efficiency of transpiration increased with increasing fertility, especially for grain production. It will also be observed that applications of manure resulted in a proportionately greater increase in the efficiency of transpiration in the relatively infertile soils.

TABLE 8. RELATIVE DRY MATTER, EAR WEIGHT, AND TRANSPIRATION COEFFICIENTS OF CORN GROWN ON DIFFERENT SOIL TYPES WITH AND WITHOUT APPLICATIONS OF MANURE (compiled from results given by Kiesselbach)

Character of Soil	*Dry Matter per Plant, in Grams*		*Total Water Transpired per Plant, in Kilograms*		*Grams of Water Used per Gram of Dry Matter*	
	Without Manure	With Manure	Without Manure	With Manure	Without Manure	With Manure
	Based on entire plant					
Infertile	128	370	57.76	119.63	463	323
Intermediate	257	426	91.87	130.44	384	308
Fertile	344	460	107.51	137.83	327	298
	Based on dry weight ears					
Infertile	54	192	—	—	1223	623
Intermediate	121	219	—	—	861	599
Fertile	181	246	—	—	634	563

The results presented in Table 8 show definitely that the plants grown on the soils of higher fertility used considerably greater quantities of water than did those grown on the series of lower fertility. This is to be expected. However, in the application of the results to existing conditions in the field it is important to keep in mind that these results were produced under conditions of optimum soil moisture content for the entire period of growth. This is not always the case in the field. It must therefore be pointed out again that the maintenance of a proper balance, established in part by plant nutrient additions to the soil, is of vital importance to adaptation and economy in the use of available moisture. A high fertility, especially if unbalanced and conducive to excessive production of vegetative development, need therefore not always be correlated with a high efficiency of transpiration. Nitrogen

fertilizers must for this reason be used with caution in dry areas. The overstimulation of plants during the early portion of the season, when moisture is available, may lead to disaster later when the amount of moisture becomes insufficient to support the luxuriant growth produced. Thus Leather (10) found in India that while the application of commercial fertilizers and manures decreased the transpiration coefficients of plants grown in controlled experiments they had no marked effect in increasing the efficiency of transpiration of plants grown in the field.

The effects of systems of cropping on the efficiency of transpiration are sometimes pronounced. Thus Thom and Holtz (18) report that wheat following wheat in the Palouse area had a transpiration coefficient of 518, as compared to 341 for wheat after fallow. In another instance the transpiration coefficient for wheat following wheat was 487, as compared to 400, 391, 360, and 310 for wheat following oats, alfalfa, corn, and clover, respectively. Widtsoe (20) found a transpiration ratio of 512 for corn following three years of fallow, while continuous corn gave a coefficient of 593.

Plant Characteristics. It has been shown that certain plants have a higher or lower transpiration coefficient than others when grown under the same soil and climatic conditions. It is hard to account for these differences. One statement can be made, however, that the causes are more or less correlated with adaptation characteristics. These characteristics may be of a morphological, chemical, or development nature. The time element as related to the course of development of the plants in question is no doubt a factor that should not be left out of consideration. This has been referred to under the discussion of factors associated with drought resistance. The questions of efficiency of transpiration and drought resistance should not be confused. The one deals with the use of water made by plants, the other with the reaction of plants faced with a scarcity of available water.

Certain steps can be taken by producers in influencing the course of development of plants so that the water available may be utilized to the best advantage. In this, factors associated with relative root development merit attention. In humid areas and under irrigation rates of seeding of all crops are higher than in dry locations. Dense stands result in interplant competition and serve to limit the extent of root development and penetration. Kiesselbach

suggests that thinner plantings may lead to a more efficient use of water because they may serve to overcome the possible detrimental effects of higher levels of soil fertility and the associated greater development of plants beyond the point justified by the amount of water present in the soil during later phases of growth. Reduced rates of seeding not only favor a greater individual development per plant but also result in most instances in a lower amount of vegetative growth to be supported per unit of area during the early portion of the season. As a result less water is removed from the soil during early phases of development. Furthermore, relative root development of plants is more or less correlated with individual top growth of plants.

Von Seelhorst (14) and von Seelhorst and Tucker (15) pointed out that an abundant supply of moisture in the soil tends to limit root penetration of cereals. This agrees with the later work reported by Weaver (19). Harris (6) showed in tests with corn and wheat that "the ratio of tops to roots was affected by soil moisture even during the germination stage."

Crop plants produced in dry areas have generally a smaller top growth than those produced under humid conditions. This is due mainly to the greater amounts of moisture available to them in the humid than in dry areas, but also in part to the varieties grown. Dwarf types of plants show in most instances a more favorable ratio of absorbing to transpiring surfaces. Sorauer (17), as early as 1880, pointed out that plants held back in their growth by limited amounts of moisture, while having a smaller absolute root system than plants grown under optimum soil moisture conditions, had, nevertheless, a greater relative root system. Von Seelhorst and Tucker report a ratio of roots to total harvest of 1:5.41, 1:8.95, and 1:9.41 for oat plants grown with small, medium, and large amounts of water. When a complete fertilizer was added to the soil the ratios became even wider, being 1:6.80, 1:13.13, and 1:15.68 for the plants grown with small, medium, and large amounts of water, respectively.

The efficiency of transpiration may to some extent be modified by structural modifications of the leaves, by surface modifications, and especially by the chlorophyll content of the leaves. The amount of water transpired by plants is largely a function of the area of leaf surface exposed to the elements. Since the efficiency

of assimilation is closely dependent on the chlorophyll content per unit area of the leaves, the relationship between chlorophyll content and efficiency of transpiration is apparent. Lundegårdh (11) found that leaves with a high chlorophyll content assimilate more per unit of area than leaves low in chlorophyll.

Effects of Crop Varieties. Variations in the efficiency of transpiration of different plants are correlated more or less with the characteristics of larger groups such as genera, less with those of species, and even less with varietal differences of plants of the same species. Varieties with similar courses of development show as a rule no consistent statistically significant differences.

The Seasonal March of Transpiration. The transpiring surfaces of plants increase with the advance of the season, and also the intensity of the climatic factors favoring transpiration. In most plants the maximum vegetative growth is attained during the middle of summer when the intensities of the climatic factors favoring transpiration are at their highest level. The transpiration rate then decreases with the reduction of active leaf surface as the plant approaches maturity.

The above gives the general course of the seasonal march of transpiration. The rate of water loss from the plant for any given interval of time is dependent on the leaf area exposed and the intensity of the climatic factors. There is also a daily march of transpiration. The general topic of seasonal march of transpiration is mentioned here to bring out the fact that plants generally pass through a period of stress as they develop their maximum leaf areas. Depending upon the phenological mean, this phase of development is often associated with the critical period of crop plants. Thus Briggs and Shantz (4) show that during a ten-day period of maximum transpiration at Akron, Colorado, annual crops lost about one-fourth of the total water lost during the season.

EFFICIENCY OF TRANSPIRATION AND DROUGHT RESISTANCE

The Application of Efficiency of Transpiration Studies to Field Conditions. The early assumptions of Briggs and Shantz (2) that determinations of transpiration ratios and information relating to the efficiency of transpiration of plants would be of interest

and value to agriculture and particularly to crop producers in areas with limited rainfall is fully justified. But the extensive experimental work on this subject has given no complete evidence that plants expending water most productively are necessarily best adapted to regions with a limited water supply. As stated earlier in this chapter, the problems of efficiency of transpiration and drought resistance, while related, should not be confused; the one deals with utilization of water by plants grown in a favorable environment as far as moisture relationships are concerned, the other with the reactions of plants faced either with a scarcity of water in the soil or with excessive losses of water to the atmosphere.

Efficiency of Transpiration Based on a Ratio. As has been pointed out previously in this chapter, it is necessary to keep in mind that studies relating to the efficiency of transpiration of plants are definitely based on a ratio of dry matter produced to amounts of water transpired in the assimilation of such dry matter. Factors influencing the amount of dry matter produced by a plant in its cycle of development enter into the determination of the transpiration ratio as much as the amount of water transpired. Transpiration is influenced in its intensities by a variety of factors. It is not a simple function. Rates of assimilation, also, are not determined by single climatic or edaphic factors but rather by a great variety of environmental conditions. To complicate matters still more, drought manifests itself in a variety of fashions. Considering all these factors, it is not altogether surprising that no direct correlation exists between the transpiration coefficients and the degrees of drought resistance of given crop plants.

The Transpiration Ratio as an Index of Ecological Status. Even though the relationship between the efficiency of transpiration and drought resistance is not so close as was formerly supposed, the transpiration ratio is of definite ecological value. This is well brought out in the following paragraph taken from Maximov's book, *The Plant in Relation to Water.*

> "Having thus established the lack of direct proportionality between the efficiency of transpiration and the degree of drought resistance, we cannot go to the opposite extreme and assert that the degree of efficiency affords no indication of the ecological character of a plant. On the contrary, owing to its relative constancy, the magnitude of the efficiency of transpiration affords one of the most satisfactory tests of

the ecological status of a plant. It is, indeed, the expression of the correlation between two most important physiological processes — the accumulation of dry substance and the expenditure of water."

The topic of drought resistance has always had a great popular appeal. Much has been written about the breeding of drought-resistant plants without due recognition of the physiological limitations of the plants considered. Many fond hopes have been blasted. Transpiration-ratio studies show that plants must transpire large quantities of water to produce limited amounts of dry matter. It takes water to make the desert bloom.

REFERENCES

1. Briggs, I. J., and H. L. Shantz, "The water requirement of plants: I, Investigations in the Great Plains in 1910 and 1911," *U. S. Dept. Agr., Bur. Plant Indus., Bull.* 284, 1913.
2. ———, "The water requirements of plants: II, A review of the literature," *U. S. Dept. Agr., Bur. Plant Ind., Bull.* 285, 1913.
3. ———, "Relative water requirement of plants," *Jour. Agr. Res.*, 3:1–64 (1914).
4. ———, "Daily transpiration during the normal growth period and its correlation with the weather," *Jour. Agr. Res.*, 7:155–212 (1916).
5. Dillman, A. C., "The water requirements of certain crop plants and weeds in the Northern Great Plains," *Jour. Agr. Res.*, 42:187–238 (1931).
6. Harris, F. S., "The effect of soil moisture, plant food, and age on the ratio of tops to roots in plants," *Jour. Amer. Soc. Agron.*, 6:65–75 (1914).
7. Hughes, H. D., and E. R. Henson, *Crop Production.* Macmillan, New York, 1930.
8. Kiesselbach, T. A., "Transpiration as a factor in crop production," *Nebr. Agr. Exp. Sta. Res. Bull.* 6, 1915.
9. ———, and E. G. Montgomery, "The relation of climatic factors to the water used by the corn plant," *Nebr. Agr. Exp. Sta. Ann. Rpt.* 24, 1910, p. 94.
10. Leather, J. W., "Water requirements of crops in India," *Mem. Dept. Agr. India, Chem. Ser.*, 1:133–184 (1910).
11. Lundegårdh, H., *Klima und Boden in ihrer Wirkung auf das Pflanzenleben.* Gustav Fischer, Jena, 1925.
12. Maximov, N. A., *The Plant in Relation to Water*, authorized trans. by R. H. Yapp. Allen & Unwin, London, 1935.

13. Pfeiffer, T., A. Rippel, and C. Photenhauer, "Über den Einfluss von Durstperioden auf das Wachtum der Pflanzen," *Landw. Ver. Stat.*, 96:353–363 (1920).
14. Seelhorst, C. von., "Die Bedeutung des Wassers im Leben der Kulturpflanzen," *Jour. f. Landw.*, 59:259–291 (1911).
15. ———, and M. Tucker, "Der Einfluss welchen der Wassergehalt und der Reichtum des Bodens auf die Ausbildung der Wurzeln und der oberirdischen Organe der Haferpflanze ausüben," *Jour. f. Landw.*, 46:52–63 (1898).
16. Shantz, H. L., and L. N. Piemeisel, "The water requirements of plants at Akron, Colo.," *Jour. Agr. Res.*, 34:1093–1190 (1927).
17. Sorauer, D., *Die Krankheiten der Pflanzen.* Breslau, 1880.
18. Thom, C. C., and H. F. Holtz, "Factors influencing the water requirements of plants," *Wash. Agr. Exp. Sta. Bull.* 146, 1917.
19. Weaver, J. E., *Root Development of Field Crops.* McGraw-Hill, New York, 1926.
20. Widtsoe, J. A., "Irrigation investigations," *Utah Agr. Exp. Sta. Bull.* 105, 1909.

Chapter XV

SPECIAL RESPONSES OF CROP PLANTS TO THE MOISTURE FACTOR

The Response of Plants to Any Single Isolated Climatic Factor. Growth may be considered as a summation of the responses to an environmental complex. It is necessary to keep in mind, however, that responses to the climatic factor must be regarded as composite reactions to the climatic variables. Under given environmental conditions a specific climatic factor may exert a more immediate and a more readily measurable response than other factors. This is especially noticeable during phases of development that are recognized as critical. If it could be assumed that the transpiration of a given amount of water by plants growing in different environments would result always in the building up of identical amounts of dry matter, there would be little necessity of evaluating precipitation effectiveness except that various methods may succeed in reflecting water losses through sources other than transpiration.

A good illustration of this is presented by Rose (28) in the results of correlation studies of climatic factors in relation to corn yields. In the heart of the Corn Belt, correlations with yield of single climatic factors, such as rainfall and temperature, failed to give significant values; that is, variations in any one factor in this area had but slight effects on corn yields. Multiple correlations, that is, the consideration of several factors in their effects on yields, gave more significant coefficients.

Moisture and the Ecological Optimum. It was brought out in Chapter IX that the region of the ecological optimum for the production of a particular crop is indicated by the performance of that crop relative to the amplitude and stability of its yield. The availability of moisture throughout the period of growth, especially during critical periods, is directly related to yield performance. Furthermore, when the moisture-yield relationships are consid-

ered over a period of years it becomes evident that the stability of moisture availability is reflected on the stability of the seasonal yields obtained. This broad conception of the ecological optimum is supported by the results of correlating yields of corn with climatic factors in the Corn Belt as reported by Rose. In the center of the Corn Belt the coefficients of correlation between July rainfall and corn yields are insignificant, fluctuating mostly between 0.00 to 0.20. This should not be interpreted to mean that an abundance of moisture is unnecessary for successful corn production in this area; rather, such low coefficients indicate that the existing moisture conditions approach the optimum for the crop.

In the moderate and minimal regions of corn production the degrees of correlation between climatic factors in general, the availability of moisture in particular, and yield performance are significant and in places even critical. That is, as the threshold of the moderate area is crossed and the minimal region entered, the crop becomes more dependent on existing moisture conditions than in the optimal region. This same condition applies also to temperature conditions and, to a somewhat less marked degree, to combinations of climatic factors.

The Importance of Moisture in Minimal Regions. Moisture is an important factor in all crop producing areas. It is the all-important factor in the minimal regions, where the average or normal rainfall is generally necessary for successfui crop production. In such areas the systems of crop production must be correlated more or less with existing moisture conditions; as a matter of fact, the entire program of crop production is more or less dominated by the moisture factor. The hopes of producers for bonanza crops are realized in those particular seasons when moisture receipts are considerably above normal, with factors influencing the loss of moisture from the soil and also from the plants at relatively low levels. Seasons with an abundance of rain are usually somewhat cooler than drought years so that the moisture received not only provides the plants with more water but also makes for better utilization of the moisture received. This statement of a general fact will hold true especially if considered in connection with the critical periods of the plants involved.

While hope for the occurrence of bonanza years constitutes one of the imoortant social features of crop production in dry areas,

such optimism is often negated by the fact that dry climates are notoriously variable. A variation of but a few inches from the normal may spell the difference between success and failure in dry climates while significantly higher deviations from the average may have but minor effects or no effect at all on the crop yields obtained in the optimum regions of humid climates. This is forcefully brought out by Mathews and Brown (20). These investigators give the annual estimated yields of winter wheat at each of 43 precipitation stations located in the southern Great Plains area; the stations were grouped according to the amounts of their annual average precipitation.

The lowest rainfall station, less than 13 inches of annual precipitation, is represented by Las Animas, Colorado. The estimated percentage of failures was 81; the expectancy of failure is 4 years out of 5. "The utter impossibility of profitably producing wheat under those rainfall conditions is fully recognized." Even the next rainfall group, 13 to 14.9 inches, constitutes extremely hazardous conditions in that the crop may be expected to fail 3 years out of 5. More than one-half of the crops may be expected to result in failures in the 15- to 15.9-inch group with an expectancy of only 1 good crop in 5 years. The group with 16 to 16.9 inches of precipitation still shows more than 2 failures in 5 years; the number of good crops to be expected has, however, increased to 1 in 4 years. The number of good crops to be expected does not increase materially until the 17- to 17.9-inch group is reached; however, the number of failures in 5 years still remains at 2. The percentage of good crops is further increased at that group of stations with average precipitations of from 18 to 18.9 inches, yet 3 failures due to drought may be expected in 10 years. At the highest rainfall stations, 19 inches or more per annum, the number of good crops is increased rapidly; still 1 year out of 4 can be expected to result in failures.

The facts pointed out in Chapter XIII relative to factors determining the efficiency of precipitation must be kept definitely in mind in any attempted application of the findings of Mathews and Brown to any region other than the southern Great Plains area. The performance of wheat at similar rainfall stations in the Pacific Northwest would be quite different for each rainfall group than in Oklahoma or Kansas primarily because of the pronounced

differences in temperature, evaporation, and seasonal distribution of rainfall.

In the light of the data presented by Mathews and Brown the point emphasized by Shantz (34), in dealing with moisture relationships in the short-grass plains, to the effect that "average rainfall alone gives almost no idea of conditions favorable or unfavorable for crop production," is entirely too comprehensive. Even though crop failures sometimes do occur during years with high rainfall, such seasons are exceptional. Before moisture can be used efficiently it must be available first of all. Thus, Cole (9), in investigating correlations between annual precipitation and the yield of spring wheat in the Great Plains, comes to the conclusion that "the years when distribution of the precipitation exercises a major control of yield as compared with the control exercised by the quantity of precipitations are relatively few."

Calculations of Yields of Wheat on the Basis of the Amount of Water Used by the Crop. The interesting relationships of seasonal precipitation to yields of wheat given by Mathews and Brown were based on estimated yields. These investigators found correlations of 0.70 ± 0.049 and 0.827 ± 0.037 between the quantity of water used by the crops and yields at Colby and Garden City, Kansas, respectively. The term "water used" refers to the amount of water, expressed in inches, removed from the soil from seeding time to harvest, plus precipitation received during that period. Yield and precipitation data for 16 years during the period, 1915–1934, were available for analysis at Colby. The derivation of the equation for calculating yields of winter wheat on the basis of the amount of water used by the crop is given by the authors in the following paragraph.

> "There appears to be a definite minimum quantity of water required to produce specified yields under climatic conditions like those at Colby. No paying yield was obtained during the experiments from the use of less than 10 inches of water, no yield of as much as 20 bushels per acre was obtained from less than 14 inches of water, and no yield of as much as 30 bushels per acre was obtained from less than 17 inches of water. The following equation was used for determining yield from the quantity of water:

$$\text{Yield} = \frac{\text{Water used} - 7.13}{0.53}$$

In other words, 7.13 inches of water were required before any grain was produced. Each additional 0.53 inch of water resulted in a bushel of increased yield."

The equation set up on the basis of the data from Garden City was very similar to that for Colby:

$$\text{Yield} = \frac{\text{Water used} - 7.69}{0.50}$$

The equation

$$\text{Yield} = \frac{\text{Water used} - 7.37}{0.51}$$

was established on the basis of the combined data from the two stations.

Mathews and Brown present evidence to show that it was possible with the employment of the above formulas to estimate yields with a fair degree of accuracy. The degree of exactness with which failures were estimated was striking. Nevertheless, the formulas have certain limitations in that the relationship between water used and yield is not a straight-line regression throughout. Estimates of yields are too high for quantities of water less than 10 inches. In general, yields increased at the rate of 3.5 bushels per acre for each additional inch of water used above 10 to a maximum of 20 inches. Since the formulas are based on bad as well as good years, the yields in years of high production are generally estimated too low.

In working with the correlations between annual precipitation and the yield of spring wheat in the northern Great Plains area, Cole found a regression equation based on 272 station years of yield on precipitation:

$$\text{Yield} = (\text{precipitation} - 8.02)\ 2.19.$$

"In round numbers, 8 inches of precipitation results in a 0 yield, and the increment of yield is 2.19 bushels for each inch above that quantity." The precipitation data were taken for the crop year ending July 31.

When the number of paired variables was reduced from 272 to 30 by combining the average yield and precipitation data of all 14 stations considered for each of the 30 years of the study, rather than taking the data for each individual station and year separately,

the regression equations for all plats, plats of continuous cropping, and plats grown after fallow were as follows:

All plats:	Yield = (precipitation − 10.07) 3.19
Continuous cropping:	Yield = (precipitation − 11.02) 3.07
Plats after fallow:	Yield = (precipitation − 8.70) 2.99

It is interesting to note that both methods of analysis of the precipitation-yield data, that is, the employment of 272 and 30 paired variables, show that spring wheat is less dependent on the occurrence of precipitation during the crop year when grown in a fallow than in a continuous system of cropping.

The yield-precipitation regression equations given by Cole are not directly comparable to the yield-water-used equations given by Mathews and Brown. The yield-precipitation equations take into account only indirectly the carry-over effects of water in the soil from the previous year, but this factor enters directly into the formulation of the yield-water-used equations. Cole eliminated from his calculations all those seasons when the crop was either destroyed or heavily damaged by hail or rust. Mathews and Brown utilized all the yield data over the test period regardless of disturbances introduced by other climatic or pathological factors.

Correlation of Crop Yields and Precipitation Amounts for Specified Periods. In general, the values of coefficients of correlation between crop yields and receipts of precipitation for specified periods of time are relatively low and frequently not great enough to be of significance in humid regions. In dry regions the values are generally high but even there hardly high enough to be used for prediction purposes.

The results obtained by Rose, previously discussed, fall in line with the above statement. Smith (36) presents a wealth of data on precipitation-yield correlations.

Table 9, taken from Smith, shows the relationships of precipitation and the final yield of corn in relation to the stages of development of the crop. The highest value found of the coefficient of correlation *r* was for the ten-day period after blossoming or tassel production. From this Smith concludes that "rainfall immediately after blossoming has a very dominating effect on the yield of corn." The average date of blossoming of corn in Ohio is July 25. The close relationship of July rainfall to corn yields is brought out by Smith in his statement that "if all the years

when the rainfall for July in Ohio has been less than three inches be grouped together, it will be found that the yield of corn averaged 30.3 bushels to the acre, and when the rainfall has been five inches or more the yield has averaged 38.1 bushels to the acre. This difference of 7.8 bushels an acre means a variation of 27,300,000 bushels of corn to the state."

TABLE 9. RESULTS OF CORRELATIONS BETWEEN RAINFALL AT GIVEN PERIODS IN RELATION TO THE DEVELOPMENT OF THE CORN PLANT AND YIELD, WAUSEON, OHIO, 1893–1912 (after Smith)

Period	*Value of r*	
Ten days before plowing	+ 0.01	
From date of plowing to date above ground	− 0.06	
From date above ground to date of blossoming	− 0.03	
From date of blossoming to date ripe	+ 0.29	± 0.11
From 5 days before blossoming to 5 days after blossoming	+ 0.45	± 0.10
For 10 days before blossoming	+ 0.20	
For 10 days after blossoming	+ 0.74	± 0.05
For 20 days after blossoming	+ 0.57	± 0.08
For 30 days after blossoming	+ 0.46	± 0.09

Blair (5) indicates that temperature relationships may be correlated more directly with spring wheat yields in eastern North and South Dakota than moisture conditions. Correlations between rainfall and wheat yields show only moderate values, while lower than normal temperatures show greater relationships to the yields obtained. High June temperatures have especially depressing effects on yields. Such high temperatures, of course, call for less efficient expenditures of water.

Cole gives the mean precipitation, average yields of spring wheat, correlation of these two variables, and the regression of yield on precipitation at 14 stations in the northern and 5 stations in the central and southern Great Plains area for the number of years specified at each during the 30-year period 1906–1935. According to Fisher's z test (10), the precipitation-yield correlations are high enough to be significant at all stations except Hettinger, North Dakota.

Before leaving this topic it is necessary to point out again that higher correlations between precipitation and yields are more in evidence for the minimal than for the optimal areas of produc-

tion. This is well illustrated by the results reported by Henney (11) dealing with precipitation and wheat yields in the nine crop-reporting districts of Kansas. In taking the northern third of Kansas crop-reporting districts 1, 2, and 3 — insignificant indices of correlations were in evidence in the eastern portion of the state, that is, in district 3; in the central third, district 2, the September-November index was + 0.825; while in the western third of the state, district 1, the index of correlation between precipitation for September, October, and November and wheat yields was + 0.872.

Koeppe (16), in correlating annual precipitation with wheat yields of Ford County, Kansas, found no general outstanding connections between these two factors in southwestern Kansas. However, when limiting his observations to specified periods, he agrees quite well with the findings of Henney, as will be recognized from the following statement from his paper: "Probably the most significant relationship was the fact that fairly moist Augusts, Septembers, Octobers, Januarys, and Februarys, and distinctly dry Aprils, were followed by good yields of wheat the following Junes or Julys." It is worth while to quote another significant remark from Koeppe's paper, especially since it sums up in a concise fashion the probable reasons for differences in the results so frequently obtained from correlation studies in two remote regions. Two probable causes for these differences in results are presumed:

> "(*a*) The difference in geographic location and consequently in physical conditions, for example, rainfall seems to be less critical in Ohio than in Kansas, because in Kansas available moisture frequently is insufficient, while in Ohio wheat rarely suffers from lack of moisture; (*b*) the interrelations of meteorological elements are so complex that it is difficult to establish, for example, whether a poor yield of wheat is due to too little rain in September, too high temperatures in October, lack of snowfall in January, too much rain in April, too strong winds in May, or whatnot else."

The above statement bears out the remark made by Chilcott (7) to the effect that "notwithstanding the fact that annual precipitation is a vital factor in determining crop yields, it is seldom, if ever, the dominant factor; but the limitation of crop yield is most frequently due to the operation of one or several inhibiting factors other than shortage of rainfall."

That drought and the factors associated with drought often cause crop failures cannot be denied. Drought, as pointed out in Chapter XII, does not consist of lack of rainfall alone. Lack of rainfall is generally associated with factors calling forth high expenditure of water by plants. Whether or not lack of rainfall is, under those conditions, referred to as "the dominant factor" is of no consequence to the end result, crop failure. In a later publication dealing more specifically with crop rotation and tillage methods in the Great Plains area, Chilcott (8) comes to the point with a very strong statement regarding the importance of soil moisture in this area by writing that "the conservation and utilization of the scanty rainfall is of such predominant importance as completely to eliminate some factors and to relegate all others to minor positions." The droughts in the Great Plains area since 1931, when the above statement was made, serve well to emphasize it in every way.

An Illustration of Precipitation — Yield Relationships in an Optimal Area. The performance record of winter wheat in the Palouse area of northern Idaho and eastern Washington as exemplified by the yields of this crop in ten different crop rotations on the University Farm at Moscow, Idaho, gives evidence that this particular area may be classified as optimal. The average yields of wheat and the coefficients of correlation between amounts of precipitation at stated intervals as well as for the entire season and annual yields are presented in Table 10 for the 22-year period 1915–1936, inclusive. All the coefficients of correlation between rainfall and yield are relatively low. The average annual rainfall during the period of the test was 21.13 inches. The fact that in excess of 50 bushels of wheat per acre can be produced on an annual average precipitation of only 21.13 inches indicates a high efficiency of moisture utilization by the wheat crop in this area. Furthermore, the seasonal variability of the yields is relatively low. The coefficient of variability is as low as 22.15 per cent in rotation number 6 and fluctuates between that value and 30.00 per cent for the better rotations. In other words, the performance record of wheat in the Palouse area shows not only high yields but also a high yield expectancy.

One of the weak points of the numerous studies of precipitation-yield relationships is that no recognition is made of the moisture

present in the soil prior to the period covered by the investigation. Such stored moisture may be very effective in the production of plants and may be a factor of considerable importance in the determination of the final yield.

TABLE 10. COEFFICIENTS OF CORRELATION BETWEEN THE WINTER WHEAT YIELDS IN TEN SYSTEMS OF CROPPING AND PRECIPITATION DURING FOUR MONTH PERIODS AND FOR THE ENTIRE CROP YEAR ON THE UNIVERSITY FARM, MOSCOW, IDAHO, FOR THE 22-YEAR PERIOD 1915–1936, INCLUSIVE

Rotation Number and Sequence of Cropping	*Average Yield of Wheat in Bushels per Acre*	*Coefficients of Correlation*			
		Late Summer and Fall — Aug. 1–Nov. 30	Winter, Dec. 1–Mar. 31	Spring and Early Summer, April 1–July 31	Entire Season, Sept. 1–Aug. 31
1. Wheat, oats, peas plus manure	52.5	0.42 ± 0.12	0.17 ± 0.14	0.06 ± 0.14	0.41 ± 0.12
2. Wheat, oats, peas	42.9	0.47 ± 0.11	0.10 ± 0.14	0.09 ± 0.15	0.41 ± 0.12
3. Wheat, oats, fallow plus manure	56.0	0.42 ± 0.12	0.20 ± 0.14	0.02 ± 0.14	0.39 ± 0.12
4. Wheat, oats, fallow	52.2	0.33 ± 0.13	0.08 ± 0.14	0.07 ± 0.14	0.02 ± 0.14
5. Wheat, oats, corn plus manure	49.4	0.42 ± 0.12	0.26 ± 0.13	0.17 ± 0.14	0.50 ± 0.11
6. Wheat plus 200 lbs. $NaNO_3$, oats, corn	47.4	0.52 ± 0.11	0.15 ± 0.14	0.28 ± 0.13	0.40 ± 0.12
7. Wheat, oats, corn	34.2	0.43 ± 0.12	0.29 ± 0.13	0.32 ± 0.13	0.58 ± 0.08
8. Wheat, oats, potatoes	49.4	0.28 ± 0.13	0.05 ± 0.14	0.02 ± 0.14	0.23 ± 0.14
11. Continuous wheat plus manure	33.8	0.33 ± 0.13	0.22 ± 0.14	0.40 ± 0.12	0.53 ± 0.10
12. Continuous wheat	23.0	0.29 ± 0.13	0.09 ± 0.14	0.58 ± 0.10	0.48 ± 0.11
Average value of r	—	0.39 ± 0.13	0.15 ± 0.06	0.20 ± 0.08	0.40 ± 0.13

Sievers and Holtz (35) point out that precipitation when in excess of 18 inches per annum does not become a limiting factor to crop production in the Palouse area. The above correlation studies bear out this contention. Seely (33) found no correlation of yield with total seasonal rainfall at the Washington Agricultural Experiment Station at Pullman. Contrasted to this, at Lind, 70 miles west of Pullman, annual precipitation constituted the largest single factor determining the yield of wheat. The average annual precipitation at Pullman of 19.80 compared to 8.02 inches at Lind illustrates well the differences in rainfall-yield correlations in optimal and minimal areas.

The Water Factor in Relation to the Degree of Correlation between the Yields of Separate Crops. Klages (14), in dealing with the variability in the yields of field crops in the states of the Mississippi Valley, pointed out material differences in the degrees of correlation shown between the average yields of separate crops in the various states of that great agricultural region. The correlations between the yields of the separate crops vary in most instances with the geographical position of the several states. The states of the Great Plains show higher values as a rule for the coefficients of correlation between the yields of individual crops than states to the east of this moisture tension area. High coefficients for the western states are in evidence, especially for those crops growing throughout the same part of the season, as between the yields of oats and barley, or spring wheat and barley or oats. The yields of corn and wheat in no case show very significant correlations. This is to be expected in view of the fact that the critical periods in the development of these two respective crops fall at entirely different times.

The same point was illustrated by Klages (15) for the degrees of correlation between the annual yields of six different cereal crops grown at the South Dakota Agricultural Experiment Station at Brookings, in the extreme eastern, and at the Highmore Substation, in the central part of the state. Moisture conditions in eastern South Dakota may be designated as moderate, while the central portion of the state can well be classified as a minimal area. The values of r were in all instances higher in the minimal than in the moderate area.

Seely correlated the yields of two varieties of wheat, Baart and Bluestem, at Pullman and Lind, Washington. For a 10-year period the value of r at Pullman was 0.741, as compared to a value of 0.961 for a 17-year period at Lind. The growth habits of these two varieties differ materially, but even with that, the differences in the degrees of correlation at Pullman, a relatively humid area, and at Lind, a very dry area, are pronounced.

Climatic, and especially moisture, conditions favoring one crop in relatively dry areas prove favorable to other crops to a greater extent in such areas than in more humid environments. Likewise, conditions leading to a reduced yield of one crop are more likely to result in reduced yields of other crops in dry areas, with their

more rigorous and often erratic climates, than in the humid areas with generally more uniform climatic conditions. This condition holds true especially in cases where the critical periods of the crops concerned nearly coincide.

Cardinal Points for Water. Sufficient evidence has been presented to show that at least a minimum amount of water must be present in the soil for the preservation of plant life. There is also an optimum or a moisture level at which plants over a period of time may be expected to give a maximum response. Furthermore, there is a maximum. When the water content of a soil increases above the optimum, it begins by degrees to interfere with the normal process in the soil and growth suffers accordingly.

The exact location of the cardinal points is determined by a variety of factors such as the specific requirements of the plants grown, the age of the plants, type of soil, and the constellation of the environmental factors especially as they affect the need for moisture during any given time interval. Since so many factors are involved, the cardinal points for water are generally not so distinct as are temperature relationships.

Table 11, taken from Mitscherlich (26), serves well to illustrate the above. The maximum yields of spring rye were obtained when the soil contained 60 per cent of its water-holding capacity. In the other crops given, the highest yields were obtained at 80 per cent of the water-holding capacity of the soil. Yields declined rapidly beyond the optimum.

TABLE 11. RELATIVE YIELDS OF DESIGNATED PLANTS GROWN ON SOILS OF VARYING MOISTURE CONTENTS (after Mitscherlich)

Crop	*Water Content in Percentage of Water-Holding Capacity*				
	20	40	60	80	100
Spring rye	30.7	71.4	92.8	77.6	19.7
Peas	14.1	50.3	87.4	100.0	9.3
Horsebeans	16.0	48.4	63.9	100.0	33.8
Potatoes	15.8	48.3	89.0	100.0	62.5

According to Kolkunov's experiments, reported by Maximov (21), different pure-line selections of a given crop, in this case

Beloturka wheat, may show quite different reactions to the moisture factor.

The yield data reported by Mitscherlich and Kolkunov do not support the statement made by Willcox (37) in his *A B C of Agrobiology*. Willcox makes free use of Mitscherlich's data and comes on the basis of it to the conclusion that "when the moisture content of the soil is 100 per cent plants are growing at the fastest possible rate." Mitscherlich (25) grew plants with increasing amounts of water but at the same time increased the volume of soil available to the plants. What Willcox took for a moisture content of 100 per cent was the full water-holding capacity of the soil less the amount of the hygroscopic capacity; consequently the soil used was not saturated.

The effects of excessive amounts of moisture in the soil lead directly and indirectly to difficulties. The most immediate is a lack of soil aeration limiting the supply of oxygen to plant roots. The second factor is that carbon dioxide accumulates in nonaerated soils and produces toxic effects. As indicated by Russell (29), plants vary considerably in their sensitiveness to these factors. They do not all stand in equal need of oxygen for their roots.

According to Livingston and Free (18), "the exclusion of oxygen from the roots of most plants interferes with the respiration of the protoplasm of the root cells, resulting in its death and the consequent failure of the roots to function as absorbers for the plant. The cessation of water intake is soon followed by the progressively decreasing turgor of the shoot and leaves and finally by wilting and death."

In contrast with the "agrobiologist" the agronomist is not dealing with a "pure" science. The facts he gathers must have practical application and economic justification and must be interpreted on the basis of both immediate and future effects. Agrobiology is defined by Willcox as a "pure" science, "concerned only with the eternal verities of nature. It acknowledges no 'taint' of economics and never looks at a bill of cost or a market quotation." The agronomist cannot afford to have his field of action so closely delineated.

The Influence of Differing Quantities of Water on the Development of Cereals. The relative availability of water during different periods of growth has a pronounced effect on the develop-

ment of plants. This is well illustrated by von Seelhorst (30). His conclusions, based on a series of pot experiments with oats and spring wheat, were as stated below:

1. *The height of plants* is determined by an abundance of moisture prior to the jointing stage.
2. *The thickness of the culms* depends mainly on the availability of moisture at jointing and thereafter.
3. *The length of the panicles and spikes* is dependent upon a good supply of moisture at jointing.
4. *The number of branches of the panicle* are determined primarily by a good supply of moisture during the early phases of growth.
5. *The development of a large number of spikelets per panicle or spike* is favored by the same factors favoring length of the panicles and spikes.
6. *The number of florets per spikelet* is dependent upon an abundant supply of moisture following jointing.
7. *The weight of grain per panicle or spike* is influenced by the same factors determining yield.
8. *The weight of 100 kernels* was about equal for the continuously low and high moisture lots; it was the lowest where an abundance of moisture was available during the early phases of vegetation followed by reduced moisture after jointing.
9. *The specific gravity of kernels* was lower where an abundance of moisture was available at flowering and thereafter than for those lots grown with less moisture during the later phases of development. Under extreme moisture conditions during the later phases of growth the specific weight of the grain may be expected to be low.
10. *The percentage of hull* was less in the continuously dry lots than in those receiving more moisture. A strong development of the panicles is apparently associated with the production of heavy hulls.
11. *The percentage of nitrogen* was highest in the lot grown with limited moisture.
12. *The weight of grain harvested* is determined primarily by an abundance of moisture at the time of jointing and flowering.
13. *The relationship of yield of grain to straw* is influenced by the availability of moisture, especially during the later phases of growth. An abundant supply of moisture at the time of jointing increases the yield of both grain and straw.

Critical Periods. The findings of von Seelhorst serve well to illustrate the need of moisture by cereal crops during the jointing, flowering, and early filling stages. Since an available supply of moisture at the shooting or the jointing stage is essential to the production of high yields, this period in the development of cereals can be designated as critical.

Von Seelhorst's pot experiments and also the experiments of von Seelhorst and Tucker (32) are well supported by the data reported by Kezer and Robertson (13) based on small field plat tests. The outstanding results of Kezer and Robertson's studies on critical periods with spring wheat under controlled irrigation conditions are presented in the following paragraph.

> "The time of applying irrigation water is an important factor in spring wheat production. Water applied at 'jointing' increases the yield of straw and grain but not the quality of the grain as indicated by bushel weight and weight per 1,000 kernels. When water is applied at 'heading,' slightly lower yields of grain and straw are obtained than when water is applied at 'jointing.' But the quality of grain is materially improved as indicated by bushel weight and weight per 1,000 kernels. Irrigation as late as 'blossoming' and 'filling' has very little effect on yields of grain or straw, but has a marked effect on grain quality as indicated by weight per measured bushel. Late irrigations at 'heading,' 'blossoming,' and 'filling' have a residual effect on the following crop. Early irrigations at 'germination' and 'tillering' increase the straw yield to a greater extent than the grain yield but produce a grain of poor quality. Irrigations of small amounts (1 inch) distributed through the growing season give the best results but are impractical."

Miller and Duley (24) showed in the case of corn that "the production of grain depended more than any other part of the plant upon a plentiful supply of moisture during the last 30-day period of growth." This last 30-day period here referred to corresponded to the phase in the growth of the crop when the more advanced plants began to tassel.

The reader should not come to the conclusion that critical periods in the production of crop plants are limited to the later phases of development. Their occurrence is definitely associated with the phenological means of climatic phenomena for given areas. Thus, in the southern Great Plains area wheat encounters a critical period immediately after seeding, or even before seeding, in that moisture may be lacking to bring about germination or emergence.

Critical periods may also develop on account of an excess of moisture, especially during the postheading periods of cereals. Such conditions lead to reduced quality and lodging and, if combined with proper temperatures, to crop damage from various fungus pests. "In humid areas," states Carleton (6), "it is not so much an excess of rainfall that causes an inferior quality of kernel as the great humidity and lack of sunshine." Von Seelhorst and

Krzymowski (31) studied the relationship of soil moisture to the delay of maturity in cereals.

Drought Reactions of Wheat. As pointed out in Chapter XII, drought is a complex phenomenon. The topic is again brought up to show that plants and even plants of the same species, wheat for instance, exhibit quite different reactions with regard to the water deficits produced in their structures by droughty conditions. It is known that given varieties will produce greater yields under conditions of stress with regard to the moisture factor than others, even though their respective stages of development are so comparable that these differences in reactions cannot be explained on the basis of drought escape. In this connection Bayles *et al.* (4) call attention to the fact "that the ability of wheat plants to produce grain under drought conditions might be due to two somewhat distinct phenomena, viz., (*a*) the ability to limit transpiration and to carry on the processes of photosynthesis and assimilation under conditions conducive to high evaporation, and (*b*) the ability of the root systems to take in moisture as fast or faster than it is transpired. . . . It would seem logical, that varieties and species might differ in one or both of these respects and also in resistance to high temperatures."

Aamodt (1) described a drought chamber to be used in the evaluation of drought resistance in plants.

TABLE 12. RATE OF WATER LOSS FROM PLANTS OF EIGHT VARIETIES OF SPRING WHEAT UPON REMOVAL FROM THE SOIL (after Bayles, *et al.*)

Variety	*Percentage of Water Remaining in Plants after the Number of Hours of Drying Indicated*				
	0	4 hrs.	22 hrs.	28 hrs.	48 hrs.
Kubanka . . .	88.8	85.9	75.7	72.3	60.7
Baart	88.6	85.2	70.0	65.4	51.9
Onas	88.6	83.7	65.9	61.5	49.7
Ceres	88.1	83.5	64.5	59.5	43.3
Marquis	88.4	83.8	61.9	56.2	43.9
Huston	87.8	82.6	61.0	56.2	43.4
Hope	88.4	82.5	58.6	53.7	42.8
Hope-Ceres . . .	88.2	81.9	56.7	50.6	38.9

Table 12, reported by Bayles *et al.*, gives the rates of water lost from the plants of eight varieties of spring wheat grown in a green-

house at 75°F and with optimum soil moisture conditions. The plants were pulled from the soil and dried at a temperature of 77°F. The table shows the percentage of water remaining in the plants after the number of hours of drying indicated.

The field performance of these varieties under drought conditions is well correlated with their respective losses of moisture as reported in Table 12. Hope and Hope-Ceres are known to lack in drought resistance, while Kubanka and Baart are well adapted to areas with low atmospheric humidity and relatively high temperatures. This would indicate that the specific structural modifications, differences in chemical composition of the cell saps, or functional causes, *i.e.*, differences in behavior of the stomata of these more drought-resistant varieties are instrumental in slowing down rates of water losses from the tissues of the plants, within significant limits.

Kolkunov (17) investigated the relationship of size and number of stomata of wheat varieties possessing varying degrees of drought resistance, and found the more resistant varieties to be characterized by small stomata. Maximov reports a later study by Kolkunov in which four pure lines of Beloturka wheat differing in cell size were grown under high and low soil moisture conditions. Under high soil moisture conditions, the larger celled varieties produced the highest grain yields, while the reverse was true under low soil moisture conditions. Pavlov (27) reports that, in general, the more drought-resistant and early-maturing varieties of winter wheat had small stomata; no such relationships were apparent, however, in spring wheat and oats.

Aamodt and Johnston (2) found, upon comparing certain physiological and morphological features of two fairly drought-resisting Russian varieties of wheat, Milturum and Caesium, with the characteristics of commonly grown varieties of spring wheat, that the relatively greater drought-resistant qualities of these two outstanding Russian varieties could be accounted for by specific differences in their growth characteristics.

Comparative Drought Resistance of Corn and the Sorghums. The sorghums as a group occupy a unique position in that they may be designated as the most drought-resistant of field crops. The special characteristics of this group of plants merit the attention of students of ecological relationships of crop plants. Corn and the

sorghums have similar growth habits, are similar in size and appearance, and are grown under comparable cultural conditions. Because of recognized greater drought resistance the sorghums are grown extensively in drier territories than corn. Nevertheless there is considerable overlapping in the producing areas of these two important crops.

The main outstanding difference between the two crops is that corn has a very definite critical period with regard to both moisture and temperature relationships at the time of tasseling. While the yields of sorghums are also influenced to a marked degree by unfavorable climatic conditions at flowering, the sorghums have one decided advantage over corn in that they are not forced ahead during periods unfavorable to growth. The ability of the sorghums to remain in an almost quiescent stage, or enter into a period of anabiosis, as Maximov chooses to call it, when confronted with conditions unfavorable to growth is outstanding and of great value to the plant. When revived by rain, a vigorous growth rate is resumed, unless, of course, conditions are too severe. Thus, the sorghums may make at least a partial grain crop under conditions of interrupted growth, under which corn would either perish or, if such drought periods occurred at the time of tasseling, produce but a low grade of fodder on account of interference with fertilization. Hot dry weather at the time corn develops tassels hastens the shedding of the pollen before the silks emerge from the husks.

Martin (19) expresses the opinion that sorghum stalks revive from a dormancy produced by drought chiefly because they have not wilted beyond recovery. In that connection special xerophytic structures, such as small cells, a waxy cuticle, and a high osmotic pressure come definitely into play. Another factor of great importance in the sorghums is the dormancy of the basal buds during periods of drought and their ability to develop into tillers rapidly enough to produce a crop of grain after moisture becomes available. Thus, Martin states that

> "frequently the suckers have produced a good crop of grain after the main stalks have died from extreme drought. Corn plants, even of suckering types, apparently lack the ability to develop fruitful tillers after the main stalks have perished from drought. The viability of the tiller buds of sorghum plants may be maintained partly because of the slow drying of sorghum stalks. The relatively higher osmotic concen-

tration of the juices of sorghum crowns and roots as compared with corn may be of some importance. A short drought followed by rains usually causes a temporary dormancy in the sorghum stalks which already have developed, while a prolonged drought followed by rains kills the old stalks yet permits a crop of 'suckers' to develop."

Another difference between these crops is the variations in the development of their root systems. Miller (22) found that for a given stage of growth Pride of Saline corn possessed the same number of primary roots as Dwarf milo and Blackhull kafir, also that the depth of penetration and spread of the roots of these three crop plants were the same. The sorghums, however, had more efficient root systems in that they "possessed approximately twice as many secondary roots per unit of primary root as did the corn plant."

Kearney and Shantz (12) suggest that the slow rate of growth of sorghum plants early in the season may help in the conservation of the soil moisture which is needed later.

In considering the rates of transpiration of corn and sorghums, Miller and Coffman (23) found that corn always transpired more water per plant during any given period than any of the sorghums tested. The amount of water transpired per plant, however, was not proportional to the extent of leaf surface. The rates of transpiration per unit of leaf surface for the sorghums were considerably higher than those of corn. They state:

"The results of these experiments seem to indicate that in most cases a small leaf surface is the most important factor in reducing the loss of water from these plants. The corn plant is not capable of supplying its large extent of leaf surface with a sufficient amount of water to satisfy the evaporating power of the air, and as a result its rate of transpiration per unit of leaf surface falls below what it would be if the needed amount of water were supplied. The sorghums, on the other hand, with their small leaf surface are able to supply water in amounts sufficient to satisfy the evaporating power of the air, and, as a result, their rate of transpiration per unit of leaf surface is higher than that of the corn."

The smaller leaf area of the sorghums, together with the fact that they possess more efficient root systems than corn, as indicated by the greater development of secondary roots, places them in an advantageous position in that a highly efficient absorbing surface has to supply water for a smaller transpiring area. This condition

more than makes up for their higher rate of transpiration per unit of leaf area.

Types of Cropping in Relation to the Moisture Factor. In humid areas continuous cropping is the rule; fallows are instituted for reasons other than conservation of moisture. In dry areas crops are grown with the intervention of fallows, the purpose being to store in the soil as much as possible of the moisture received during the fallow year so that it may be used by the next crop grown. The frequency of fallows necessary to attain profitable yields depends on the amount of the annual precipitation, the efficiency of precipitation, and also on the seasonal distribution of the moisture received. Under extreme conditions crops are grown in alternate crop, fallow systems. In other instances a fallow every third year may suffice.

Fallows are most effective in areas with winter and early spring precipitation. It is difficult to conserve moisture supplied by summer rains, especially when such rains come in light showers. A good fallow not only must be fairly effective in the conservation of moisture already in the soil when cultural operations are started, it also must leave the surface of the soil so that moisture falling during the fallow period may enter readily and thus not be lost by immediate evaporation. In the past the importance of soil mulches has been overemphasized. While they were fairly effective in retaining moisture in the soil at the time the fallow was instituted, they left the surface layer in a deflocculated condition so that considerable resistance was offered to the penetration of moisture. Aside from the question of penetration of moisture, a deflocculated soil condition brought about by frequent workings of the soil to leave the surface finely pulverized is too conducive to soil erosion either by wind or water to be justified.

Fertility and structure are factors to be considered in all soils. In dry areas moisture is the main and not infrequently the only factor limiting crop production. Consequently, cropping systems in such areas must be arranged with due regard to the ever-important factor of moisture conservation. Crops usually exhausting all available soil moisture during any one season should be selected with care and incorporated into a cropping system with due consideration of the likely effects on other crops to follow. Thus, Baker and Klages (3) report a yield of winter wheat in a wheat,

oats, sunflower rotation of 25.9 bushels as compared to a yield of 35.5 bushels per acre when the wheat was grown in a wheat, oats, corn rotation. The inclusion of a high soil-moisture-removing crop such as sunflowers in a rotation system in the Palouse area served to reduce the wheat yield by 9.6 bushels per acre.

REFERENCES

1. Aamodt, O. S., "A machine for testing the resistance of plants to injury by atmospheric drought," *Can. Jour. Res.*, 12:788–795 (1935).
2. ———, and W. H. Johnston, "Studies on drought resistance in spring wheat," *Can. Jour. Res.*, 14:122–152 (1936).
3. Baker, G. O., and K. H. W. Klages, "Crop rotation studies," *Idaho Agr. Exp. Sta. Bull.* 227, 1938.
4. Bayles, B. B., J. W. Taylor, and A. T. Bartel, "Rate of water loss in wheat varieties and resistance to artificial drouth," *Jour. Amer. Soc. Agron.*, 29:40–52 (1937).
5. Blair, T. A., "Temperature and spring wheat," *Mo. Wea. Rev.*, Jan., 1915.
6. Carleton, M. A., *The Small Grains.* Macmillan, New York, 1916.
7. Chilcott, E. C., "The relations between crop yields and precipitation in the Great Plains area," *U. S. Dept. Agr. Misc. Circ.* 81, 1927.
8. ———, "The relations between crop yields and precipitation in the Great Plains area," *U. S. Dept. Agr. Misc. Circ.* 81, Supplement 1, Crop rotations and tillage methods, 1931.
9. Cole, J. S., "Correlations between annual precipitation and the yield of spring wheat in the Great Plains," *U. S. Dept. Agr. Tech. Bull.* 636, 1938.
10. Fisher, R. A., *Statistical Methods for Research Workers.* Oliver and Boyd, London, 1936.
11. Henney, H. J., "Estimation of future wheat production from rainfall," *Mo. Wea. Rev.*, 63:185–187 (1935).
12. Kearney, T. H., and H. L. Shantz, "The water economy of dry-land crops," *U. S. Dept. Agr. Yearbook* 1911:351–362 (1912).
13. Kezer, A., and D. W. Robertson, "The critical period of applying irrigation water to wheat," *Jour. Amer. Soc. Agron.*, 19:80–116 (1927).
14. Klages, K. H. W., "Geographical distribution of variability in the yields of field crops in the states of the Mississippi Valley," *Ecology*, 11:293–306 (1930).
15. ———, "Geographical distribution of variability in the yields of cereal crops in South Dakota," *Ecology*, 12:334–345 (1931).

16. Koeppe, C. E., "Meteorological conditions and wheat yields in Ford county, Kansas," *Mo. Wea. Rev.*, 62:132–133 (1934).
17. Kolkunov, V. R., "The role of selection in the study of drought," *Int. Rev. Sci. & Pract. Agr.*, 12:386–390 (1926).
18. Livingston, B. E., and E. E. Free, "The effect of deficient soil oxygen on the roots of higher plants," *The Johns Hopkins Univ. Circ.* 1917:380 (1917).
19. Martin, J. H., "The comparative drought resistance of sorghums and corn," *Jour. Amer. Soc. Agron.*, 22:993–1003 (1930).
20. Mathews, O. R., and L. A. Brown, "Winter wheat and sorghum production in the Southern Great Plains under limited rainfall," *U. S. Dept. Agr. Circ.* 477, 1938.
21. Maximov, N. A., *The Plant in Relation to Water*, authorized trans. ed. with notes by R. H. Yapp. Allen and Unwin, London, 1928.
22. Miller, E. C., "Comparative study of the root systems and leaf areas of corn and the sorghums," *Jour. Agr. Res.*, 6:311–332 (1916).
23. ———, and W. B. Coffman, "Comparative transpiration of corn and the sorghums," *Jour. Agr. Res.*, 13:579–604 (1918).
24. Miller, M. F., and F. L. Duley, "The effect of a varying moisture supply upon the development and composition of the maize plant at different periods of growth," *Mo. Agr. Exp. Sta. Res. Bull.* 76, 1925.
25. Mitscherlich, E. A., *Bodenkunde für Land — und Forstwirte.* 2d ed., Paul Parey, Berlin, 1913.
26. ———, *Bodenkunde für Land — und Forstwirte.* 3d ed., Paul Parey, Berlin, 1920.
27. Pavlov, K., "Results of investigations on the number, size of stomata and osmotic pressure as an aid in the determination of the physiological properties of wheat and oats varieties produced by the breeder, with particular reference to their resistance to drought," *Sbornik* (annals) *Ceskoslov. Acad. Zemed.*, 6:565–616 [Abstract in *Plant Breed. Abstr.* 2 (3)]:120, entry 396 (1932).
28. Rose, J. K., "Corn yield and climate in the Corn Belt," *Geog. Rev.*, 26:88–102 (1936).
29. Russell, E. J., *Soil Conditions and Plant Growth.* 6th ed., Longmans, London, 1935.
30. Seelhorst, C. von., "Neuer Beitrag zur Frage des Einflusses des Wassergehalts des Bodens auf die Entwicklung der Pflanzen," *Jour. f. Landw.*, 48:165–177 (1900).
31. ———, and Krzymowski, "Das Reifen verschiedener Sommerweizen-varietaten bei verschiedener Bodenfeuchtigkeit," *Jour. f. Landw.*, 57:113–115 (1909).

32. Seelhorst, C. von, and M. Tucker, "Der Einfluss welchen der Wassergehalt und der Reichtum des Bodens auf die Ausbildung der Wurzeln und der oberirdischen Organe der Haferpflanze ausüben, "*Jour. f. Landw.*, 46:52–63 (1898).
33. Seely, C. I., "The effect of moisture and temperature on the growth and yield of Baart and Bluestem wheat." Thesis, Washington State College, 1935.
34. Shantz, H. L., "Natural vegetation as an indicator of the capabilities of land for crop production in the Great Plains Area," *U. S. Dept. Agr., Bur. Plant Ind., Bull.* 201, 1911.
35. Sievers, F. J., and H. F. Holtz, "The influence of precipitation on soil composition and on soil organic matter maintenance," *Wash. Agr. Exp. Sta. Bull.* 176, 1923.
36. Smith, J. W., *Agricultural Meteorology.* Macmillan, New York, 1920.
37. Willcox, O. W., *ABC of Agrobiology.* Norton, New York, 1937.

Chapter XVI

TEMPERATURE

GENERAL ASPECTS OF THE TEMPERATURE FACTOR

Temperature Provides a Working Condition. No description of a physiological environment is complete without a notation of the existing temperature conditions. Temperature provides a working condition for nearly all plant functions. More than that, it provides the necessary energy for some processes; radiant energy, for example, is absorbed in photosynthesis and released in respiration. Certain winter-hardy plants by virtue of their structural and chemical modifications are able to survive periods of low temperatures but are unable to renew growth until proper temperatures are again established to provide the necessary working condition.

Recording of Temperatures. Temperatures for any given interval of time are evaluated readily by the expansion or contraction of a column of mercury or in some instances alcohol in the bore of a thermometer. A continuous record of temperatures is made available by the use of thermographs. Thermograph records are of considerable value. However, they do not register temperatures with the degree of accuracy or the precision of standard thermometers.

From the standpoint of plant responses, temperatures may be evaluated in the light of the mean, or average, or in relation to the extremes for any given interval of time. Extremes are recorded as minima or maxima. Temperature extremes call forth more outstanding and obvious responses than mere averages. The mean temperature for any given day is calculated from the average of the recorded minimum and maximum temperature for that day. For this special maximum and minimum, thermometers are used.

The mean or average temperature for any given day calculated from the average readings of the minimum and maximum temperatures corresponds sufficiently closely to the averages taken at more

frequent intervals, or from thermograph records, to be of practical value. It is evident that the calculation of the mean temperature for the day from the average of the minimum and maximum amounts to an approximation. For the study of detailed physiological responses readings at shorter intervals or from a calibrated thermograph record are highly desirable and often essential.

Average and Normal Temperatures. The daily normal temperatures for a station are the averages of each day of the year for a period of not less than ten years. The monthly normal consists of the average for the particular month for not less than the same length of time; the yearly normal is computed from an average of the monthly normals. Calculations of normal temperatures become more reliable and representative with increasing number of years. Normals once established seldom change materially.

Obviously the greatest fluctuations will be found in the daily normals. Certain days showing wide departures from normal seasonal trends may influence the values calculated on the basis of daily averages. The curve of the normal trend may be conveniently smoothed by means of five- or seven-day moving averages.

The comparison of temperature and also moisture conditions of any given season with the normal for the area often can be used to advantage for explaining observed crop responses. Figure 28 gives the normal monthly temperatures and monthly accumulated precipitation at Moscow, Idaho, also the average monthly temperatures and accumulations of precipitation for the crop year 1937–38, September 1 to August 31. Since winter wheat is the predominating crop of the Palouse area, the employment of the crop season gives a more concise picture of crop responses in relation to climatic conditions than could be obtained by the use of the calendar year. This particular season was exceptionally favorable for the production of winter wheat; yields on the University Farm and the region in general were high. On the other hand, the deficiency of moisture in May, June, July, and August together with the higher than normal temperatures for these months was decidedly detrimental to spring wheat. The winter wheat escaped the period of drought, brought about by low precipitation and higher than normal temperatures, serving definitely to decrease the efficiency of transpiration, while the yields of the spring wheat were low

because the critical period for this crop coincided with the period of stress induced by the indicated moisture and temperature relationships.

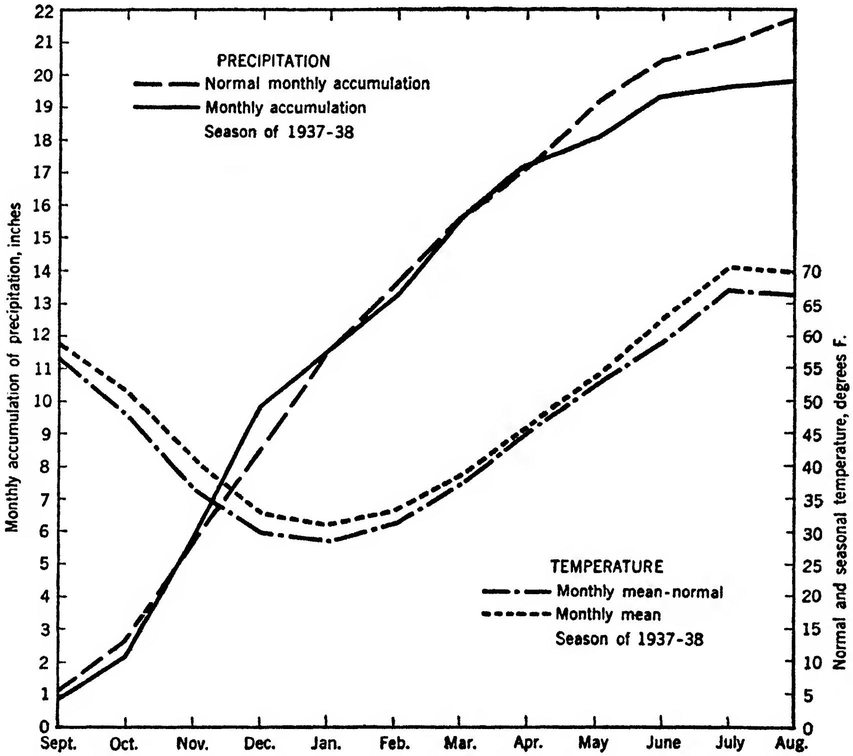


FIG. 28. Precipitation and temperature data, University Farm, Moscow, Idaho, for the crop year 1937–38 as compared with the normal. Precipitation data are presented on the basis of monthly accumulations, temperature data as monthly averages.

Length of the Growing Season. The length of the growing season is generally defined as the interval in days between the last killing frost in spring and the first killing frost in fall. A temperature depression of sufficient severity to be generally destructive to the staple crop plants of the locality is regarded as a killing frost. Frequently vegetation has not developed sufficiently in spring to be injured by frost, or the main crops of a region may be fully matured before the occurrence of the first frost in fall. It is difficult under such conditions to determine the dates of the killing frosts by

direct observations of effects on vegetation. In such cases the length of the growing season is determined by the interval between the last date in spring on which a temperature of 32°F was recorded, and the first date at which the temperature again dropped to that point in fall.

The length of the growing season for any given location may vary materially from year to year. For a 45-year period, 1893–1938, at Moscow, Idaho, the average was 149.71 days; the range extended from 83 to 192 days; the standard deviation was 24.36.

Figure 29, after Day and taken from Redway's *Handbook of Meteorology* (43), gives the length of the growing season for the different parts of the United States. More detailed maps of the length of the growing season and also of the dates of occurrence of the last killing frosts in spring and the first in fall are given by Reed (44). In the Mississippi Valley the lines show a trend from east to west, the effects of river bottoms and topographical features; proximity of large bodies of water is apparent, however. The length of the growing season is extremely variable in the various areas of the mountainous western portion of the country. These differences are accounted for by variations in elevation and in part by the influences of the Pacific Ocean and the particular topographical features enabling the influence of this large body of water to be felt inland.

Thermal and Physiological Growing Season. It will be well at this point to refer back to Chapter X, particularly to the topic of vegetation and climatic rhythms in their relation to adaptation. The term "length of growing season" is generally used, as in the previous discussion, to designate the frostfree period of any region; that is, it is determined strictly by the prevailing temperature conditions with a total disregard of the other factors of the environment. It is useful as such and has its place, but it must be recognized that it expresses only what may be designated as the thermal growing season. The growth of plants or the ability of an environment to support active growth is dependent on a constellation of factors of which temperature is but one. As a matter of fact the intensity of the temperature factor may, and in many instances does, in the course of the season, bring about the very condition throwing some other essential factor of the environment below the minimal requirements for growth. In many habitats the lack of

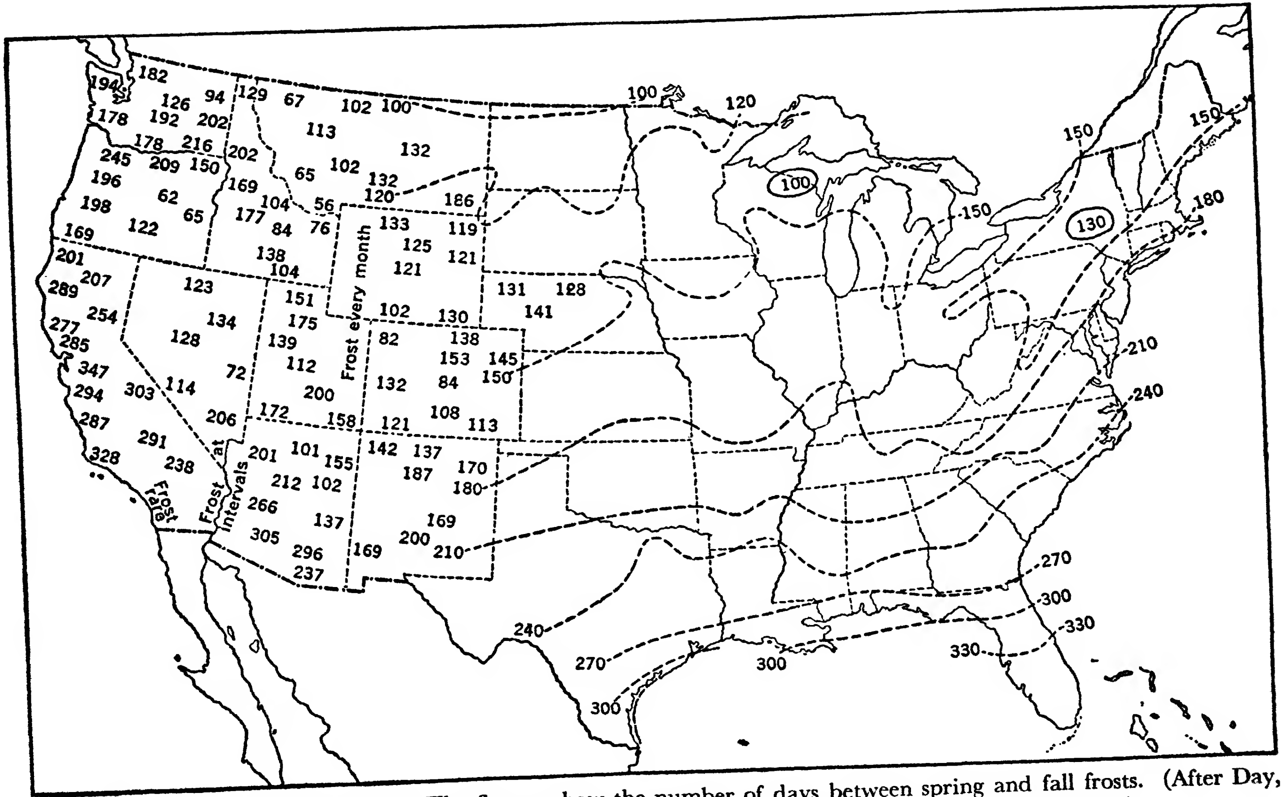


Fig. 29. Length of growing season. The figures show the number of days between spring and fall frosts. (After Day, reproduced from Redway, *Handbook of Meteorology*, by permission of John Wiley and Sons.)

moisture during the frostfree season may force vegetation into a period of dormancy so that two periods of plant activity, rather than one, may be in evidence. This is the case in the Mediterranean type of climate. Those periods when not only temperature but also the other essential factors of the environment are favorable to growth may be designated as the physiological growing season. The agronomic significance of this distinction is evident.

Thermal Belts. The effects of local topography on the occurrence of killing frosts is well illustrated by the location of warmer or "frostfree" zones on slopes or up on the sides of valleys. The down drainage of cool heavy air results, in the absence of equalizing winds, in higher temperatures at adjacent heights of moderate elevations than in the bottoms of the valleys where the cool air settles. The air on the slopes may be replaced for some time by somewhat warmer air from the higher slopes. Not infrequently a difference of as much as 10°F may be recorded between the temperature at valley bottoms and that some distance up the sides. This may result on concentric belts on the slopes where vegetation will escape frost damage. These thermal belts and the question of air drainage in general are of considerable importance in selecting areas for the production of crops subject to frost damage.

The phenomenon of the rather common occurrence of higher night and early-morning temperatures at higher rather than at lower altitudes in areas of rough topography is known in meteorology as temperature inversion.

Limits to Crop Production. Figure 30, taken from Baker (4), gives the great agricultural regions of the United States. They are designated primarily on the basis of the important crops grown in the various agricultural provinces. The six regions of the West have been given topographic and geographic names because of the dominating influence of topography and the Pacific Ocean. A comparison of Figs. 29 and 30 shows the effect of the length of the growing season and temperature in general on the location of the great agricultural regions.

Figure 31 gives the northern limits of general production of the four winter cereals in order of their respective degrees of winter-hardiness. The northern limit of winter rye production is found in the prairie provinces of Canada. Salmon (47) points out that the isotherm of 10°F for the daily minimum temperatures of January

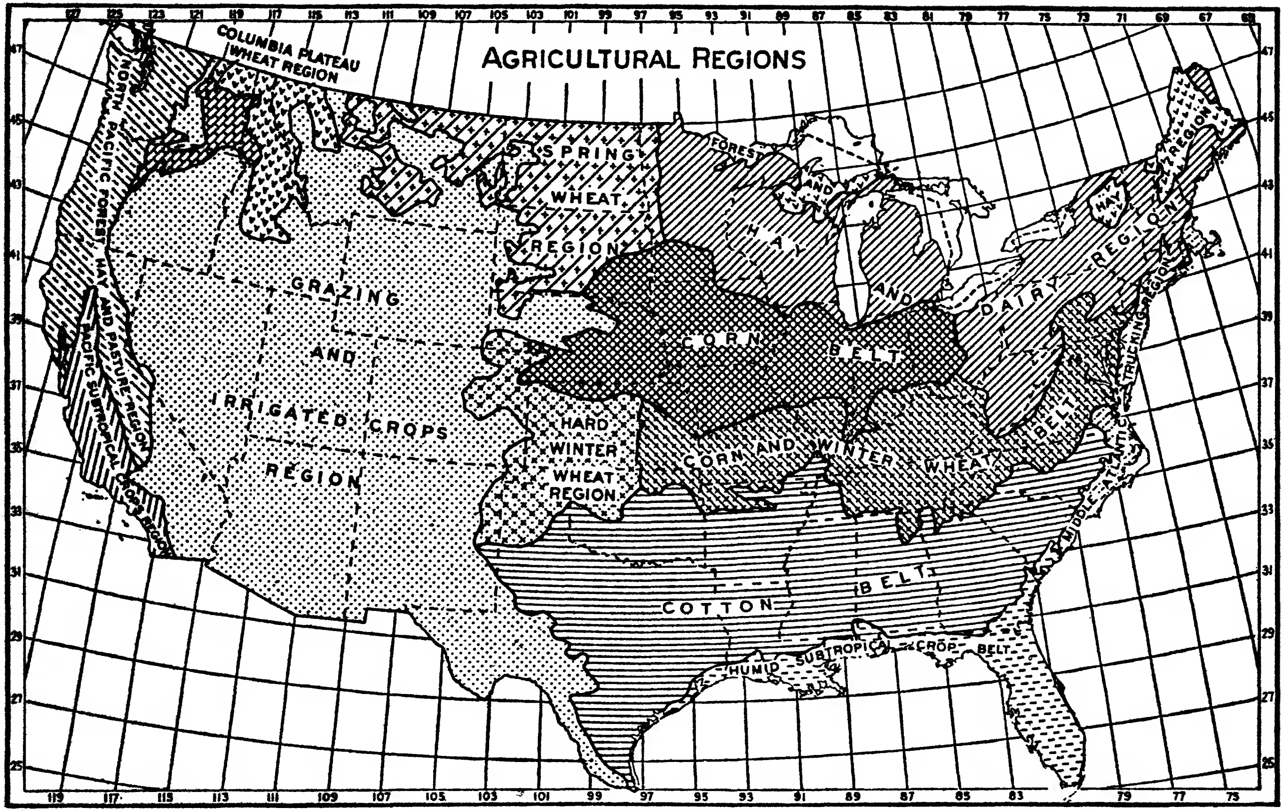


FIG. 30. The great agricultural regions of the United States. (After Baker.)

and February corresponds in general to the line separating the areas of extensive winter and spring wheat production.

The extreme northern limit of all crop production is determined almost entirely by temperature conditions. The longer length of the days at higher latitudes compensates in part for the lower average temperatures of these regions.

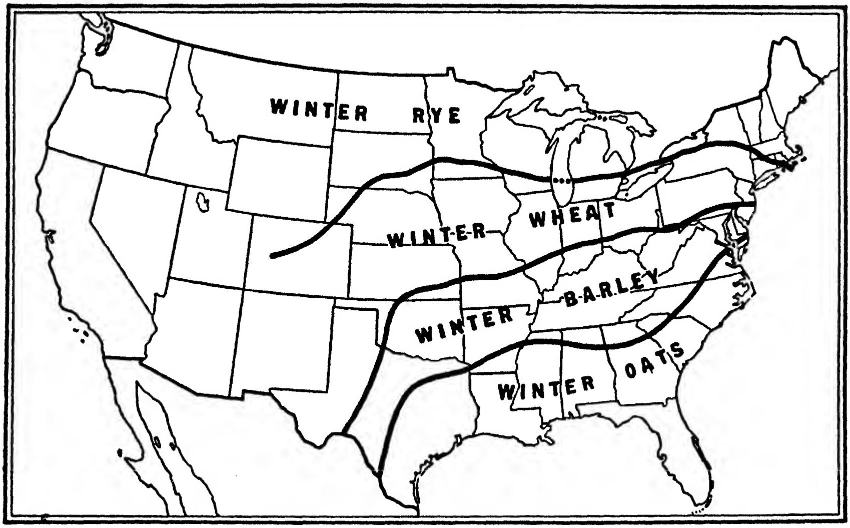


Fig. 31. The northern limits of production of winter oats, barley, wheat, and rye.

EFFECTS OF LOW TEMPERATURES

Chilling and Freezing of Plants. A summary of the extensive literature available on the effects of low temperatures on plant growth and survival would be entirely beyond the scope of this chapter. An extensive, annotated bibliography of the literature is presented by Harvey (12).

In discussing the effects of low temperatures on plant life, it is well to differentiate between the results of freezing and chilling. The discussion dealing with freezing temperatures will be presented here primarily as it relates to the winterkilling or survival of cereals and such other crop plants which ordinarily survive one or more winters. The chilling of plants, that is, exposure to temperatures that are low but above the freezing point, has decided detrimental effects, especially on certain plants of southern origin, and thus

Schaffnit found no relationship between the development of external plant characteristics and cold resistance. Schimper (53) comes out with the definite statement that the "capacity to withstand intense cold is a specific property of protoplasm and is quite unassisted by protective measures that are external." Nilsson-Ehle (37), as a result of his breeding experiments, concluded that the degree of winter-hardiness of wheat stands in no definite relation to the ordinary morphological varietal characteristics.

In contrast to the above, a considerable number of other investigators report varying degrees of correlation between certain obvious external plant characteristics and hardiness. Sinz (57) designated hardy varieties of wheat as having narrow, firm, and well-cutinized leaves. Buhlert (7) in comparing the winter-hardiness of a limited number of varieties of winter wheat and rye found that the hardy varieties, especially of the winter rye, had thicker and narrower leaves than nonhardy types. Arnin-Schlangenthin (3) points out a correlation between dwarfness and hardiness in winter wheat.

Schliephacke (54) characterizes hardy varieties of winter wheat by narrow, cuneiform leaves. He also calls attention to physiological drought as a possible factor in the winter survival of cereals. "Physiological drought," states Salmon (48), "has never been proved to be a cause of winterkilling of cereals, but has long been regarded as a cause of injury to shrubs and trees." In the same paper, however, he points out that "most of our hardy cereals such as winter rye, Turkey and Kharkof wheat, and the Winter Turf variety of oats, do have certain xerophytic structures characterized by a narrow leaf and a prostrate habit of growth. The soft winter wheats, winter barley, and common varieties of oats, on the other hand, have broad leaves which usually assume a more or less upright position and hence are more exposed to the wind." Considering the rôle of desiccation as a cause of injury in freezing and keeping in mind the outstanding characteristics of hardy varieties of cereals, most of which would serve to promote water economy in the plant, the part played by physiological drought as a contributing cause for winter injury merits attention.

Klages (18) in investigating the relationship of leaf area of winter wheat plants came to the conclusion that most hardy varieties have comparatively small leaf areas. Though not an infallible index to

hardiness because of the great variety of factors that may lead to winter injury, leaf area, nevertheless, is a characteristic worthy of consideration in the selection of hardy types of winter wheat. It is entirely possible that the degree of association between exposed leaf surface and hardiness may be closer in semiarid than in humid areas. A dry atmosphere during the winter months when the ground is frozen puts winter annuals to a severe test.

Habit of Growth. Hardy varieties of winter wheat are commonly believed to have a more or less procumbent habit of growth (Salmon, 48, Summerby, 61, and Schmidt, 55). While this is generally true and readily explained on the basis of less exposure to desiccating winds, some notable unconformities prevent the utilization of this particular varietal characteristic as an absolute criterion of hardiness.

Klages (18) pointed out that while differences in habits of growth do not stand in absolute relationship to hardiness, an erect growth habit of seedlings during the fall and winter months is a better indicator of lack of resistance than a recumbent habit of growth an indicator of hardiness.

Profuse tillering has frequently been associated with hardiness. No such relationship was found, however, by Barulina (5) or Klages (18).

Anatomical Features. Molisch (30) and Müller-Thurgau (32) expressed the opinion that the microscopic minuteness of the plant cell had to be considered, at least to a certain degree, as a protective means against the effects of low temperatures.

Nonhardy varieties of wheat generally have larger cells than the hardy wheats of the Turkey type; however, this is but one of the numerous differences between these types. On the other hand, firmness of leaves and in part highly cutinized leaves are not infrequently associated with a small compact cellular structure.

Rate of Growth. "Any treatment materially checking the growth of plants," states Rosa (45), "increases cold resistance." Horticulturists have long recognized the importance of dormancy, and reduced activity, as a protective measure against frost injury. It would appear, then, that hardy varieties of winter wheat should show a slower rate of growth than nonhardy types. This was found to be generally true by Buhlert (7) and Hedlund (13). Wallén (65) pointed out the undesirability of high autumn temperatures in

relation to the winter survival of wheat in southern Sweden. Such supranormal temperatures would of course lead to increased activity on the part of fall-sown wheat. Klages (18) found that hardy varieties of winter wheat generally showed a less rapid rate of growth in the field in autumn than did nonhardy types.

Chemical Factors. Since the lowering of the freezing point of a solution is directly proportional to its molecular concentration, it has been assumed by numerous investigators that the freezing point of cell sap would be lowered as its density increases. Thus Ohlweiler (38) states that extreme differences in cell sap density, in general, are accompanied by corresponding differences in their resistance to cold. Macfarlane (24) notes that "all thermo-resistant plants have a relatively dense protoplasm, or a stored mass of reserve material in their cells that contribute to their thermo-resistant qualities." Graber and his associates (10) point out the relationship of organic reserves to winter-hardiness in alfalfa. Late cutting of alfalfa lowered organic reserves to the extent that the plants were subject to severe winterkilling.

Lidforss (22) reports that the starch in plants remaining green during the winter months is converted into sugar upon the approach of low temperatures. Müller-Thurgau (33) notes the increase in the sugar content of potato tubers upon exposure to low temperatures. Åckerman and Johannson (2) report the various degrees of frost resistance of the principal Swedish wheats to be correlated with their sugar and dry-matter contents. Maximov (26) increased resistance to freezing by introducing such substances as sugar, glycerine, and alcohol into the tissues of plants.

The protective action of sugar has been accounted for, not only by its effect on lowering the freezing point of the cell sap, but also by the fact that the increased concentration of the cell sap is instrumental in decreasing water losses through transpiration.

Hooker (15) found a correlation between hardiness and the pentosan content of plants. He called attention to the great water-holding abilities of the pentosans. The water is held in an adsorbed or colloidal condition. The capacity of hardy plants to resist the desiccating effects of extreme cold was by him accounted for by the lower free but proportionately greater colloidal water content of such plants. Newton (36) found that hardened tissue of winter wheat was able to retain its water content against great force;

such tissue contained a high amount of bound water. Steinmetz (60) found that the roots of a hardy variety of alfalfa contained more sugar than those of a less hardy variety. Sugar content was expressed in terms of total carbohydrates. Steinmetz was unable to demonstrate quantitative relationships between pentosan content and hardiness in alfalfa.

Variations in Frost Resistance of Plant Parts and Effect of Age of Plants. Schaffnit found that the tips of young growing sprouts of wheat showed considerable resistance to cold. This he attributed to the presence of bud scales and to the colloidal state of certain cell contents. Martin reports the crown as the most hardy portion of wheat plants above the soil surface. Young leaves were found to be more hardy than older ones, and the bases of leaves more hardy than the tips.

Klages (17) showed that unhardened winter wheat seedlings become more susceptible to low temperatures with advance in age. This was confirmed by Suneson and Peltier (63), who showed that the "youngest plants appear to be most hardy, regardless of the type of hardening." Peltier and Kiesselbach (40) report that spring cereals "just emerging from the soil or in the one-leaf stage were found materially more resistant to cold than seedlings in the two- and three-leaf stages."

EXTERNAL FACTORS MODIFYING THE DEGREE OF FROST INJURY IN PLANTS

Rate of Freezing and Hardening. Ohlweiler brings out that the effect of cold upon vegetation in general depends largely upon the rapidity with which destructive changes in temperature are brought about, being far greater when the change takes place within narrow limits of time.

The main effect of hardening is that time and opportunity are given the plant to adjust itself to its changing environment. Thus, Salmon (48) states, "slow freezing may decrease the injury by preventing the formation of ice within the cells, by giving the tissue an opportunity to dry out and by permitting the protoplasm to adjust itself to the new condition."

That the formation of protective substances is dependent upon the rate of cooling was well illustrated by Müller-Thurgau (33). Potato tubers held at a temperature of − 1 to − 2°C contained

from 1.62 to 2.43 per cent of sugar as compared to a sugar content of 0.4 to 0.7 per cent before the hardening.

"The principal effect of the hardening process for cabbages," states Harvey (11), "is a change in the constitution of the protoplasm which prevents their precipitation as a result of the physical and chemical changes incident upon freezing."

Rate of Thawing. Death of nonhardy plants is most likely to occur during the freezing process and in cases even before freezing temperatures are reached; that is, the protoplasm is injured beyond possible repair. Pfeffer (42) observed that "a non-resistant plant is killed by the actual freezing and cannot be saved by the most careful thawing, whereas resistant plants remain living however rapidly they may be thawed."

Abbe (1) gives a good summary on the question of rate of thawing in its relation to survival in the following paragraph.

> "When the frozen plant is thawed out and evaporation is rapid, the loss of water either from the surface of the tender plant or through the stomata of the mature plant is much more rapid than under normal conditions and the plant wilts, but when there is no evaporation, the sap has time to return into the cells, and the wilting is not so severe. Therefore, it is proper to say that the injury is not done by more or less rapid thawing, but by more or less rapid evaporation that accompanies the thawing. If similar plants are thawed out under warm and cold water, respectively, the rate of thawing has no influence on its health. It is now seen that this is because in both these cases there is no special chance for evaporation, and the cell sap was able to go back into the cells; the contrary occurs when the plant thaws in the open air."

Alternate Freezing and Thawing. Lamb (21) aptly points out that winter-hardiness is often loosely considered synonymous with cold resistance when, as a matter of fact, it must be recognized that winter injury may be due to secondary effects of low temperatures, such as smothering under ice or tightly packed snow, or upheaval of the plants due to alternate freezing and thawing. It is a well-established fact that successive exposures to low temperatures are more detrimental than single exposures.

Heaving. "In the soft wheat belt of the Northeastern United States, it is only in exceptional seasons," states Lamb, "that winter wheat is killed by the direct effects of low temperature. In the opinion of workers long associated with this area, the most common

cause of injury is probably heaving; that is, the pulling of the plants from the soil when the surface is raised up by frost action."

An excellent review of the mechanics of heaving and the conditions necessary for its occurrence is given by Münichsdorfer (34). Heaving of soil is not a simple physical process occasioned by the transformation of soil water from the liquid to the solid state. Maximum raising of the surface soil takes place under conditions favoring the separation of ice layers in the surface soil mass. The raising of the soil surface is almost entirely due to the formation of the ice layers and is practically equal to the sum of the thickness of these layers.

The control or possible reduction of heaving injury may be approached from the soil and plant angles. The water table of the soil may be lowered by proper drainage. Winter annual crops may be planted early to allow strong crown and basal foliage growth to blanket the soil so that surface temperature fluctuations may be reduced. Lamb was able to measure slight differences in the extensibility and breaking tension of roots of varieties of winter wheat. Kokkonen (20) reports definite association between tensile strength and extensibility of the roots of winter rye and winter survival in Finland. Heaving damage in alfalfa and clovers may be reduced by allowing the plants to enter the winter months with a sufficient top growth to modify surface soil temperatures.

Soil Moisture and Soil Type. Because of the higher specific heat of water, 1.000, as compared to that of soil particles, 0.193 for sand, 0.206 for clay, and 0.215 for loam, a soil containing a large amount of water will cool down less rapidly than a drier soil but, for the same reason, will warm up more slowly. Bouyoucos (6) found that the temperatures of different soil types were remarkably alike throughout the summer, fall, and winter months. The greatest differences appear in spring, that is, during thawing. Thus, sand and gravel thaw first, followed by clay and loam one or two days later and by peat 10 or 15 days later.

Under field conditions the temperature of moist soils is less subject than dry soils to wide fluctuations at moderately low temperatures. After soils are once frozen, temperature fluctuations will not differ greatly. Salmon (49) sums up his investigations of the relationship of soil moisture and soil type to winterkilling with the statement that

"a sandy soil is colder and the survival of plants growing upon it less than a dry clay or loam soil, and also colder than a wet clay or a wet loam during those seasons when the ground remains unfrozen much of the time. It appears probable that a dry sand is colder during the winter than a wet sand regardless of the character of the season, but a dry clay or silt loam is colder than a wet soil of the same kind only when the ground remains unfrozen."

Hunt (16) states that the loamy soils of the Corn Belt, which are usually friable and well supplied with organic matter but often poorly drained, are not so well adapted to winter wheat as are the clay uplands; wheat on the former soils is more likely to winterkill in unfavorable seasons. Hunt here refers to damage from heaving which is definitely favored by wet soils and conditions conducive to good capillary movement of water.

Sorauer (59) observed dry parts of fields to suffer more from frost than moist areas.

Protection of Winter Annual Crops. Various means have been used from time to time to create a more favorable environment for winter annual plants during periods of stress. One of the most effective methods is to provide a favorable place in the rotation for the winter annual so that the plants may be protected to some extent by the remains of the previously grown crop. A good example of this is the planting of winter wheat in standing corn stalks or on stubble land with a minimum of disturbance to the stubble so that they may serve to protect the wheat plants during the winter. Klages (19) reports a yield of 21.5 bushels and only 1 crop failure in 18 years due to winterkilling of wheat having the protection of ten-inch-high stubble of checked corn as compared to a yield of only 13.1 bushels per acre and 5 crop failures due to winterkilling in the case of the crop grown in a similar rotation but following oats, after the harvesting of which the land was plowed. The corn stubble provided little protection, but enough to reduce the velocity of the wind to some extent and thus reduce water losses from the leaves of the wheat plants either by the direct protection or, in years with snowfall, by catching and holding a snow cover.

Furrow drills are used in certain areas for the double purpose of placing the seed in contact with soil moisture and for providing protection for the seedlings against drying winds.

EFFECTS OF HIGH TEMPERATURES

External Temperatures in Relation to Plant Temperatures. In most plants the temperatures of the various plant parts do not differ materially from those of the surrounding air or medium. Fleshy leaves may at times have a temperature materially higher than those of the surrounding atmosphere. Ursprung (64) found the surface of the leaves of *Sempervivum* to attain a temperature of 18 to 25°C higher than that of the surrounding air in sunlight. Owing to the thickness and nature of such leaves, the heat they absorbed cannot be dissipated as readily by air currents or radiation as in the case of ordinary leaves.

Miller and Saunders (28) found that the temperatures of the upper surfaces of leaves of corn, sorghum, cowpeas, soybeans, watermelon, and pumpkin growing under field conditions in Kansas were essentially the same as those of the surrounding air. The leaves of alfalfa, on the other hand, showed under the same condition a temperature of less than 1°C below that of the air. In the case of the plants enumerated above the heat absorbed is quickly utilized in transpiration or rapidly disseminated into the surrounding air, so that the temperature of the leaves approximated that of the air. "In the case of alfalfa the rate of transpiration is evidently rapid enough to reduce the temperature of the leaf slightly below that of the air.

In diffuse light, turgid leaves show a temperature somewhat below that of the atmosphere. Air currents have a tendency to lower the temperature of leaves in direct sunlight. Smith (58) observed that breezes reduce the temperature of leaves in sunlight by from 2 to 10°C. Obviously thin leaves are more noticeably affected than thick ones. The leaves of crop plants, states Miller (27), respond quickly to changes in air temperature; even slight changes are almost immediately followed by corresponding changes in the temperature of the leaves.

The temperatures of turgid and rapidly transpiring leaves under corresponding conditions of exposure are lower than those of wilted leaves or leaves in which the rate of transpiration was reduced. Miller and Saunders report a maximum difference between the wilted and turgid leaves of cowpeas of 6.7°C when the temperature of the air was 37.6°C. The transpiration of the wilted leaves was approximately only one-sixteenth that of the turgid ones.

Death Due to High Temperatures. Temperature, as pointed out earlier, provides a working condition for plant functions. The plant, however, will respond effectively, that is, it will continue to grow, only at temperatures within certain more or less specific ranges. These general limits have been taken up in the discussion of cardinal points, Chapter VIII. The response of plants within the limits set by the cardinal points will be discussed in detail in the next chapter relating to temperature efficiencies.

The growth of plants is slowed down materially upon the surpassing of the optimal temperature; it ceases beyond the maximum, but life may not be in immediate danger unless exposure to supramaximal temperatures continues for too long a period. Under field conditions it may be assumed that crop plants or portions of them are not killed by the direct effects of the temperature as such, but rather by the secondary effects induced by high temperatures such as inability of the plant to reestablish the necessary water balance, the dehydration of the protoplasm, or sometimes by a partial precipitation of the cell proteins. Generally, though not always, heat damage to crops is associated with and is most intense under a combination of drought and high temperatures. Low availability of moisture and heat occurring in combination are disastrous in that high temperatures increase the requirements for moisture by the exposed portions of the plant. If rapidly moving air currents are added to this dreaded combination, destruction is soon complete. Even hot winds alone, with an abundance of water available for the use of the plants, may be very destructive in that the ability of the plant to provide water for the rapidly transpiring more exposed portions may be taxed beyond the limit.

REFERENCES

1. Abbe, C., "The influence of cold on plants — a résumé," *U. S. Dept. Agr. Exp. Sta. Rec.*, 6:777–781 (1895).
2. Åckerman, Å., and H. Johanson, "Beiträge zur Kenntnis der Kälteresistenz des Winterweizens," *Ztschr. Pflanzenzücht*, 5:349–356 (1917).
3. Arnin-Schlangenthin, Graf, "Das Ausfrieren von Wintergetreide bei Barfrost," *Illstr. Landw. Zeit.*, 21:761–763 (1901).
4. Baker, O. E., "Agricultural maps," *U. S. Dept. Agr. Yearbook* 1928:640–665.

5. Barulina, E. I., "The winter resistance of cereals," *Izv. Saratovsk. Selsk. Khoz. Inst.* (*Ann. Inst. Agron. Saratov*), 1:42–57 (1923). Abs. in *Exp. Sta. Rec.*, 50:231–232 (1924).
6. Bouyoucos, G. J., "Soil temperature," *Mich. Agr. Exp. Sta. Tech. Bull.* 26, 1916.
7. Buhlert, "Untersuchungen über das Auswintern des Getreides," *Landw. Jahrb.*, 35:837–888 (1906).
8. Faris, J. A., "Cold chlorosis of sugar cane," *Phytopathology*, 16:885–891 (1926).
9. Gorke, H., "Über Chemische Vorgänge beim Erfrieren der Pflanzen," *Landw. Versuchssta*, 65:149–160 (1907).
10. Graber, L. F., N. T. Nelson, W. A. Leukel, and W. B. Albert, "Organic food reserves in relation to the growth of alfalfa and other perennial herbaceous plants," *Wisc. Agr. Exp. Sta. Res. Bull.* 80, 1927.
11. Harvey, R. B., "Hardening process in plants and developments from frost injury," *Jour. Agr. Res.*, 15:83–112 (1918).
12. ———, *An Annotated Bibliography of the Low Temperature Relationships of Plants.* Burgess Pub. Co., Minneapolis, 1936.
13. Hedlund, T., "Über die Möglichkeit, von der Ausbildung des Weizens in Herbst auf die Winterfestigkeit der verschiedenen Sorten zu schliessen," *Bot. Centralbl.*, 135:222–224 (1917).
14. Holbert, J. R., and W. L. Burlison, "Some questions and answers on cold injury to corn," *Ill. Farmers Institute* (unnumbered *Bull.*), 1930.
15. Hooker, H. D., "Pentosan content in relation to winter hardiness," *Proc. Amer. Soc. Hort. Sci.*, 1920:204–207.
16. Hunt, T. E., *The Cereals in America.* Orange Judd Co., New York, 1904.
17. Klages, H. H. W., "Relation of soil moisture content to resistance of wheat seedlings to low temperatures," *Jour. Amer. Soc. Agron.*, 18:184–193 (1926).
18. ———, "Metrical attributes and the physiology of hardy varieties of winter wheat," *Jour. Amer. Soc. Agron.*, 18:529–566 (1926).
19. ———, "Winter wheat production in South Dakota," *S. D. Agr. Exp. Sta. Bull.* 276, 1933.
20. Kokkonen, P., "Über das Verhältnis der Winterfestigkeit des Roggens zur Dehnbarkeit und Dehnungsfestigkeit seiner Wurzeln," *Acta Forestalia Fennica*, 33:1–46 (1927).
21. Lamb, C. A., "Tensile strength, extensibility, and other characteristics of wheat roots in relation to winter injury," *Ohio Agr. Exp. Sta. Bull.* 568, 1936.
22. Lidforss, B., "Zur Physiologie und Biologie der Wintergrünen Flora," *Bot. Centbl.*, 68:33–44 (1896).

23. Lundegårdh, H., *Klima und Boden in ihrer Wirkung auf das Pflanzenleben.* Gustav Fischer, Jena, 1925.
24. Macfarlane, J. M., The relation of plant protoplasm to its environment. *Jour. Acad. Nat. Sci. Phila.* 2, Ser. 15:135–143 (1912) (Abstr. in *Exp. Sta. Rec.*, 28:326–327 (1913).
25. Martin, J. H., "Comparative studies of winter hardiness in wheat," *Jour. Agr. Res.*, 35:493–535 (1927).
26. Maximov, N. A., "Chemische Schutzmittel der Pflanzen gegen Erfrieren," *Ver. Deut. Bot. Gesell.*, 30:52–65 (1912).
27. Miller, E. C., *Plant Physiology with Reference to Green Plants.* McGraw-Hill, New York, 1938.
28. ———, and A. R. Saunders, "Some observations on the temperature of the leaves of crop plants," *Jour. Agr. Res.*, 26:15–43 (1923).
29. Molisch, H., "Das Erfrieren von Pflanzen bei Temperaturen über den Eispunkt," *Sitzber Akad. wiss. Wien, Math. Naturw. Kl.*, 105 (1):82–95 (1896).
30. ———, *Untersuchungen über das Erfrieren der Pflanzen.* Jena, 1897.
31. ———, *Populäre biologische Vorträge.* Gustav Fischer, Jena, 1922.
32. Müller-Thurgau, H., "Über das Gefrieren und Erfrieren der Pflanzen," *Landw. Jahrb.*, 9:133–189 (1880).
33. ———, "Über Zuckeranhäufung in Pflanzenteile in Folge niederer Temperatur," *Landw. Jahrb.*, 11:751–828 (1882).
34. Münichsdorfer, F., "Die Mechanik des Bodenfrostes," *Die Ernährung der Pflanze*, 31:61–66 (1935).
35. Nelson, R., "Storage and transportational diseases of vegetables due to suboxidation," *Mich. Agr. Exp. Sta. Tech. Bull.* 81 (1926).
36. Newton, R., "A comparative study of winter wheat varieties with especial reference to winterkilling," *Jour. Agr. Sci.*, 12:1–19 (1922).
37. Nilsson-Ehle, H., "Zur Kenntnis der Erblichkeitsverhältnisse der Eigenschaft Winterfestigkeit beim Weizen," *Zeit. f. Pflanzenzüchtung*, 1:3–12 (1912).
38. Ohlweiler, W. W., "The relation between density of cell sap and freezing point of leaves," *Twenty-third Ann. Report. Mo. Bot. Gardens*, 101–131 (1912).
39. Peltier, G. L., "Control equipment for the study of hardiness in crop plants," *Jour. Agr. Res.*, 43:177–182 (1931).
40. ———, and T. A. Kiesselbach, "The comparative cold resistance of spring small grains," *Jour. Amer. Soc. Agron.*, 26:681–687 (1934).
41. ———, and H. M. Tysdal, "A method for the determination of comparative hardiness in seedling alfalfas by controlled hardening and artificial freezing," *Jour. Agr. Res.*, 44:429–444 (1932).

42. Pfeffer, W., *The Physiology of Plants*, trans. A. J. Ewart, Vol. 2. Clarendon Press, Oxford, 1903.
43. Redway, J. W., *Handbook of Meteorology.* Wiley, New York, 1921.
44. Reed, W. G., *Atlas of American Agriculture*, Pt. II, Sec. 1. "Frost and Growing Season," Gov't Printing Office, Washington, 1918.
45. Rosa, T. J., "Investigations on the hardening process in vegetable plants," *Mo. Agr. Exp. Sta. Res. Bull.* 48, 1921.
46. Sachs, J., "Untersuchungen über das Erfrieren der Pflanzen," *Landw. Versuchs-Sta.*, 2:167–201 (1860).
47. Salmon, S. C., "The relation of winter temperature to the distribution of winter and spring wheat," *Jour. Amer. Soc. Agron.*, 9:21–24 (1917).
48. ———, "Why cereals winterkill," *Jour. Amer. Soc. Agron.*, 9:353–380 (1917).
49. ———, "Relation of soil type and moisture content to temperature and winterkilling," *Science*, 47:173 (1918).
50. ———, "Resistance of varieties of winter wheat and rye to low temperatures in relation to winter hardiness and adaptation," *Kansas Agr. Exp. Sta. Tech. Bull.* 35, 1933.
51. Schaffnit, E., "Über den Einfluss niederer Temperaturen auf die pflanzliche Zelle," *Zeit. Alg. Phys.*, 12:323–336 (1912).
52. Schander, R., and E. Schaffnit, "Untersuchungen über das Auswintern des Getreides," *Landw. Jahrb.*, 52:1–66 (1918).
53. Schimper, A. F. W., *Plant Geography upon a Physiological Basis*, trans. German by W. R. Fisher. Clarendon Press, Oxford, 1903.
54. Schliephacke, K., "Ziele und Erfolge Deutscher Getreidezüchtung," *Deut. Landw. Presse*, 33:11–13 (1906).
55. Schmidt, O., "Über den Entwicklungsverlauf beim Getreide," *Landw. Jahrb.*, 45:267–324 (1913).
56. Sellschop, J. P. F., and S. C. Salmon, "The influence of chilling, above the freezing point, on certain crop plants," *Jour. Agr. Res.*, 37:315–338 (1928).
57. Sinz, E., "Beziehungen zwischen Trockensubstanz und Winterfestigkeit bei verschiedenen Winterweizen Varietäten," *Jour. f. Landw.*, 62:301–335 (1914).
58. Smith, A. M., "On the internal temperature of leaves in tropical isolation with special reference to the effect of color on the temperature," *Ann. Roy. Bot. Gard. Peradinya.*, 4:229–298 (1909).
59. Sorauer, P., "Über Frostbeschädigungen am Getreide und damit in Verbindung stehende Pilzkrankheiten," *Landw. Jahrb.*, 32:1–66 (1903).
60. Steinmetz, F. H., "Winter hardiness in alfalfa varieties," *Minn. Agr. Exp. Sta. Tech. Bull.* 38, 1926.

61. Summerby, R., "A new hardy variety of winter wheat," *Sci. Agr.*, 2:168–169 (1922).
62. Suneson, C. A., and G. L. Peltier, "Cold resistance adjustments of field-hardened winter wheat as determined by artificial freezing," *Jour. Amer. Soc. Agron.*, 26:50–58 (1934).
63. ———, "Effect of stage of seedling development upon the cold resistance of winter wheats," *Jour. Amer. Soc. Agron.*, 26:687–692 (1934).
64. Ursprung, A., "Die physikalischen Eigenschaften der Laubblätter," *Bibl. Bot.*, 60:1–120 (1903).
65. Wallén, A., "The influence of temperature and rainfall on the yields of certain kinds of wheat at Svalof and Ultuna, Sweden," *Int. Rev. Sci. & Pract. Agr.*, 12:804–808 (1921).
66. Weibel, R. O., and K. S. Quisenberry, "Field versus controlled freezing as a measure of cold resistance of winter wheat varieties," *Jour. Amer. Soc. Agron.*, 33:336–343 (1941).

Chapter XVII

TEMPERATURE EFFICIENCIES AND BIOCLIMATICS IN RELATION TO CROP DISTRIBUTION

INTRODUCTION

Numerous methods of evaluating effective temperatures have been recommended from time to time. They may be listed, going from the simpler to the more complex, as length of growing season, temperature summations or the direct index, the mean maximum, Thornthwaite's temperature efficiency index, the temperature efficiency or exponential index, the physiological index, and the moisture-temperature or hydrothermal index. Merriam's life zones may be added to the foregoing array from the historical point of view.

These various indices will be discussed in this chapter in relation to the distribution of field crops in the United States. Their physiological ramifications are interesting, but apply rather to detailed local investigations rather than to the field of general crop distribution.

TEMPERATURE EFFICIENCY INDICES

Length of Growing Season. Since data regarding the length of the physiological growing season could be calculated from the climatological data of but a limited number of stations, it is necessary to make use of the thermal growing season in the present discussion. The calculation of the comparable lengths of the physiological growing seasons of a number of widely separated stations representing not only different types of climates, but also a great variety of predominating crops, would be extremely difficult. The data for determining the length of the thermal growing season, on the other hand, are available from all weather stations keeping a record of minimum temperatures.

The evaluation of effective temperatures strictly on the basis of the length of the growing season falls short of offering a true status

of plant behaviors and responses in that it deals only with the interval in days between the last killing frost in spring and the first killing frost in fall, with a total disregard of temperature intensities in the interim. All plant activity near the freezing point is extremely low. Kincer (6) suggests the "zero of vital temperature point" at 6°C or 42.8°F. This point varies with different plants in accordance with their temperature requirements. Kincer proposes that the zero of vital temperature be taken at the temperature usually encountered at the date of the beginning of planting for the respective crops considered. These temperatures would be 37 to 40°F for spring wheat, 43°F for oats, 45°F for potatoes, 54 to 57°F for corn, and 62 to 64°F for cotton. Not infrequently, and especially in the calculation of the temperature indices to be discussed presently, a general "zero of vital temperature point" is arbitrarily placed at 40°F or 4.4°C.

Since the length of the growing season gives no direct indication of the temperature conditions in the interval of time between killing frosts the placing of this particular time unit under the heading of "temperature efficiency indices" requires a stretching of the imagination. It will be shown later, however, that while the length of the growing season, as such, may not merit classification as a temperature efficiency index, it is nevertheless of definite value in that it shows high degrees of correlation with the more complex and theoretically better fortified method of temperature evaluations. It serves very well for the general comparison of temperature conditions of widely separated regions.

Temperature Summation or the Remainder Index. The direct, also termed the "remainder," index is derived by a summation of all daily positive temperatures. Positive temperatures are those above the established zero of vital temperature point. Thus, for instance, for a day with a mean temperature of 72, the accumulation of positive temperatures would be 72 − 40 or 32.

The obvious objection to the direct index is that no recognition whatsoever is made of the increasing rates of vital processes with increases in temperature. This increase is, as has been pointed out by numerous investigators, not linear or directly proportional to the increase in the temperature, but rather (at least within certain temperature ranges) corresponds to a logarithmic curve, concave upward. Matthaei (11) showed that the rate of evolution of carbon

dioxide from leaves in darkness and also the fixation of this gas in the presence of light follows quite closely the chemical principle of van't Hoff and Arrhenius which states that the velocity of chemical reactions doubles with each increase of approximately 10°C or 18°F. Cohen (1) calculated from measurements recorded by Hertwig (4) that the rate of development of frog eggs is doubled with each increase of 10°C. The fact that the remainder index does not evaluate accurately the separate temperatures entering into its calculation in accordance with their true physiological effects is well illustrated by the wide variations found in the number of heat units required to grow a crop to maturity in different seasons in the same locality. Thus Seeley (15) reports that the heat units used by corn in Ohio varied from 1,232 to 1,919 from sprouting to flowering, and from 897 to 1,607 from flowering to maturity during a period of 27 years.

The method of direct temperature summation does not take into consideration the possible detrimental effects of supraoptimal temperatures, although it is less at fault in this respect than the exponential index in which the effects of such high temperatures are actually magnified.

Figure 33, taken from Livingston and Livingston (10), gives the temperature summations for the various areas of the United States. It will be observed that with the assumption of a "zero" point of 39°F the index for the very southern tip of Florida is given at 14,000, for southwestern Arizona at 10,000, as compared to an index of 4,000 for the northern portion of the Corn Belt.

Thornthwaite's Temperature Efficiency Index. Thornthwaite (17), in developing his temperature efficiency, or T–E, index, used in his recent classifications of climates, evaluates the effectiveness of temperatures on a linear basis. He used an empirical formula calculated to give values of the T–E index corresponding to his precipitation, or P–E, index. That is, the ranges of both of these indices extend from zero for the least favorable to 128 for the most effective temperature or rainfall. The empirical formula used by Thornthwaite is as follows:

$$I = \sum_{n=1}^{12} \frac{(T - 32)}{4} n$$

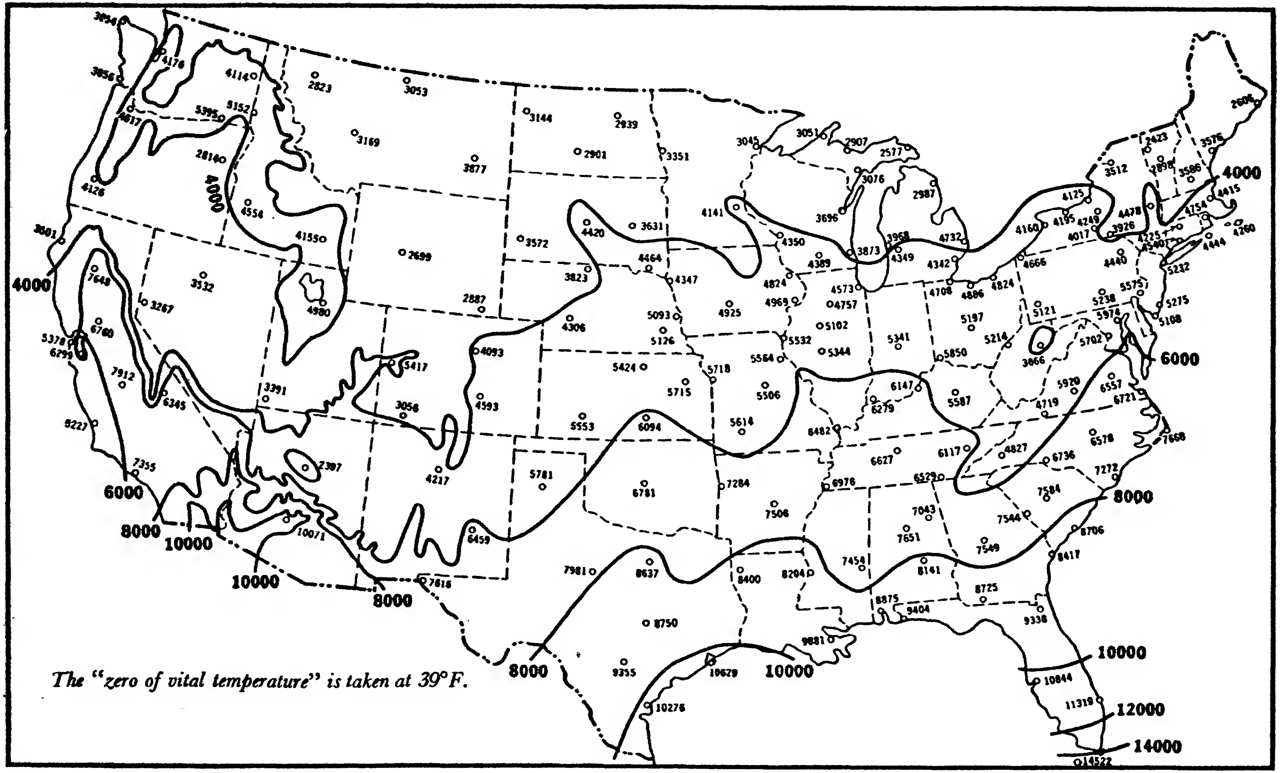


FIG. 33. The climatic zonation of the United States according to the remainder summation indices of temperature efficiency for plant growth, for the period of the average frostless season. (After Livingston and Livingston.)

In this formula I is the T–E or temperature efficiency index made up of the summation of the 12 monthly indices for the year. T represents the monthly mean temperature values in degrees Fahrenheit. (The value of 32 is used for temperatures below 32°F.)

Six temperature provinces are defined on the basis of temperature efficiency summations. These are as follows:

Temperature Provinces	*T–E Index*
A′ Tropical	128 and above
B′ Mesothermal	64 to 127
C′ Microthermal	32 to 63
D′ Taiga	16 to 31
E′ Tundra	1 to 15
F′ Frost	0

Figure 34, taken from Thornthwaite, gives the temperature provinces of the United States according to the above classification.

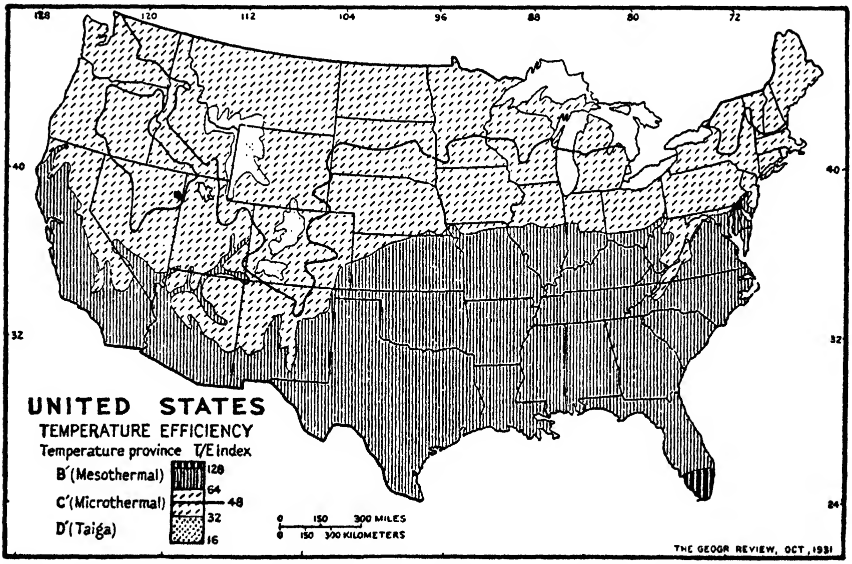


FIG. 34. Temperature efficiency provinces of the United States according to Thornthwaite's T–E index. (After Thornthwaite.)

Thornthwaite recognizes the importance of summer concentration of thermal efficiency. Five temperature subprovinces are defined. Their derivation is stated in the following two paragraphs cited from his paper.

"The T–E index incompletely expresses the temperature relations of the climate because of local differences in the annual march of tem-

perature. It is possible that in two stations having the same efficiency index one may have a gradual thermal summation throughout the whole year and the other a very rapid accumulation during a few summer months. In order to express this difference the ratio of the thermal efficiency accumulation of the three summer months to the total thermal efficiency has been calculated. Expressed in percentages these ratios range between 25 and 100, for obviously not less than 25 per cent of the total would be accumulated during the most favorable quarter of the year.

The index of summer concentration varies with latitude and with distance from the ocean. It is equivalent to annual range of temperature, but is a more significant climatic factor than annual range. Although the annual range would be the same where the temperature varies between 0°F and 40°F as where it varies between 40°F and 80°F, it is clear that the summer concentration in the latter case would be very much less than in the former."

The temperature subprovinces recommended are as follows:

Subprovince	*Percentage Summer Concentration*
a	25 to 34
b	35 to 49
c	50 to 69
d	70 to 99
e	100

The summer concentration of thermal efficiency for the United States is given in Fig. 35.

Since Thorthwaite used a linear basis of evaluating the effectiveness of temperatures, his T–E index does not differ in its application from the direct summation or remainder index and is, therefore, subject to the same criticism. It will be observed that the zero of vital activity point used is 32°F.

The Efficiency or Exponential Index. The efficiency or exponential index is based on the principle of van't Hoff and Arrhenius. The index is derived from the summation of the calculated efficiency of the mean daily temperatures for the period of the average frostfree season. The efficiency index, *u*, for each day of the growing season is calculated by Livingston and Livingston (10) from the formula:

$$u = 2^{\frac{t-40}{18}}$$

The growth rate of plants is taken at unity at 40°F and is, in accordance with the principle of van't Hoff and Arrhenius, assumed

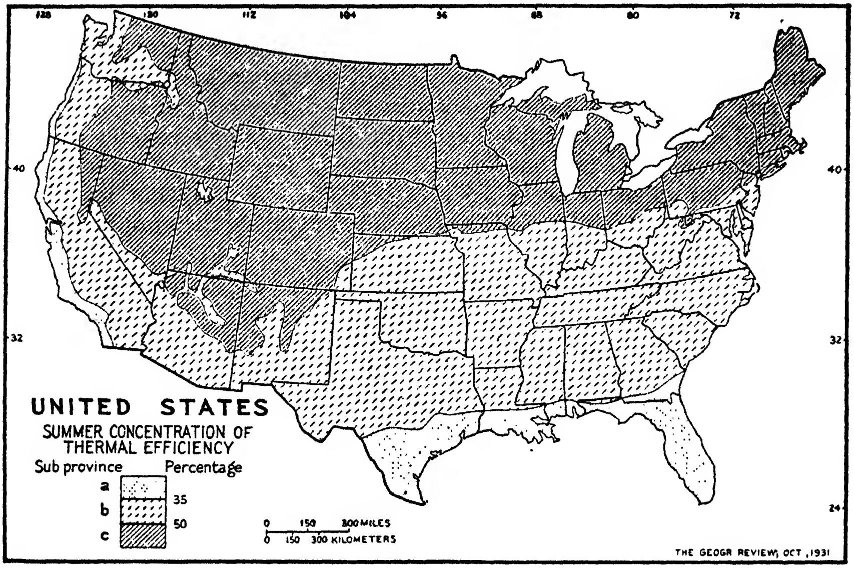


FIG. 35. The summer concentration of thermal efficiency for the United States. (After Thornthwaite.)

to double with each rise of 18°F. For fractional exponents the above equation becomes more workable when written in the form:

$$\text{Log } u = \frac{\text{Log } 2}{18} (t - 40)$$

In the two above equations, u is the daily temperature efficiency to be calculated, t represents the normal daily mean temperature on the Fahrenheit scale. The zero point of vital activity is taken at 40°F.

The temperature efficiency of a day with the mean temperature of 40°F is taken at unity; with an average temperature of 58 it doubles, and at 76 it becomes 2^2 or 4.

The exponential index overcomes the objection made to the remainder index since it recognizes that plant responses to increasing temperatures are not linear but rather, at least within moderate temperature ranges, exhibit a logarithmic curve, concave upward. The obvious fault of the exponential index is that an increasingly high efficiency is ascribed to supraoptimal temperatures during days or portions of days when the recorded temperatures may be high enough above the optimum to have decided detrimental effects.

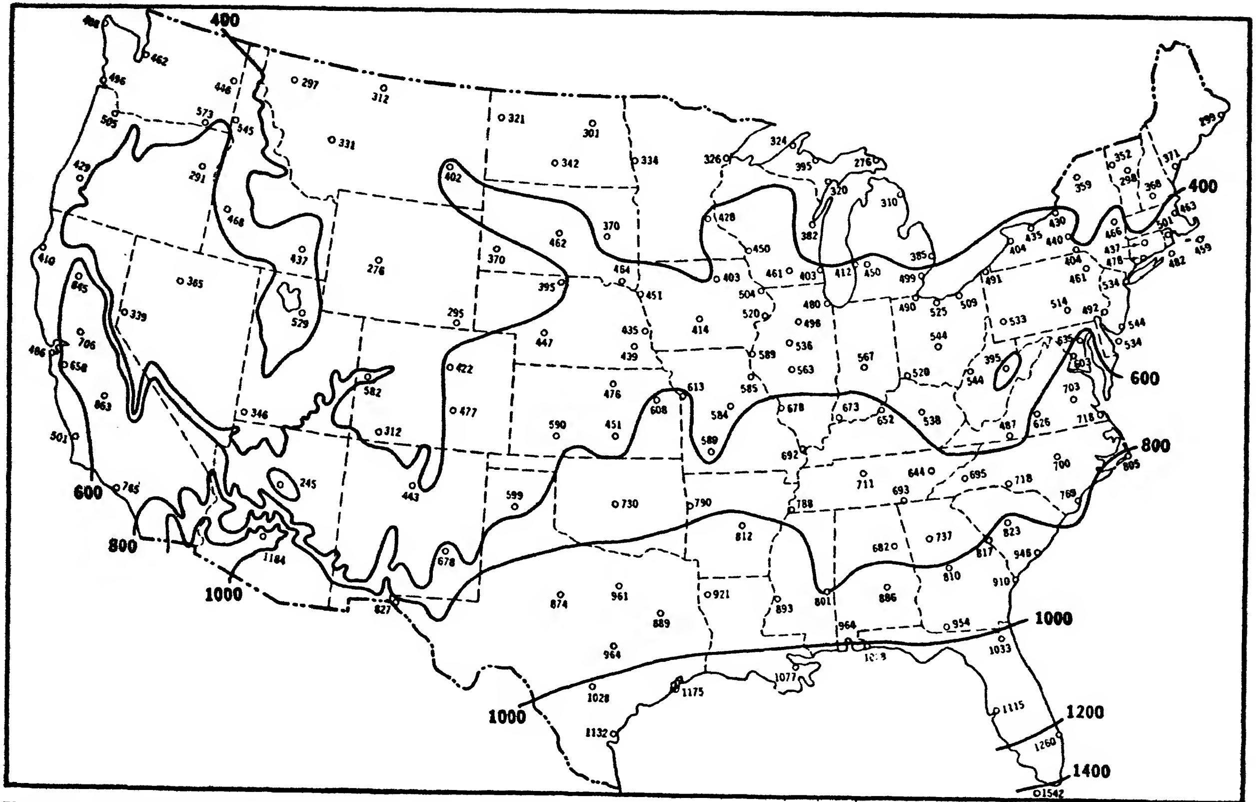


FIG. 36. Climatic zonation of the United States according to exponential summation indices of temperature efficiency for plant growth, for the period of the average frostfree season. The "zero of vital temperature" is taken at 40°F. (After Livingston.)

Figure 36, taken from Livingston and Livingston, gives the climatic zonation of the United States according to the exponential summation indices of temperature efficiency for plant growth, for the period of the average frostfree season. It will be observed that the accumulated values of the daily efficiency or exponential summation indices stand at around 1,000 units in the southern portions of the Gulf States as compared to 400 units for the northern Corn Belt and 350 units for the hard red spring wheat area.

The Physiological Index. Any discussion of the vital activities of organisms must recognize the existence of physiological limits for the various functions met with in existence and growth. It is well established that the growth rates of organisms sooner or later cease to increase and begin then to decrease with exposures to increasing temperatures. The various efficiency indices so far discussed make no allowances for the existence of the physiological limits.

The physiological temperature index is based on the researches reported by Lehenbauer (7) on the rates of elongation of maize shoots. Lehenbauer showed that the hourly rate of elongation of maize shoots exposed to maintained temperatures for a period of 12 hours was 0.09 millimeters for 12°C, 1.11 millimeters for 32°C, and 0.06 millimeters for 43°C under the conditions of his experiments. The smoothed graph of the 12-hour exposure period is used as a basis for determining the physiological indices. The graph is extended at its ends, by extrapolation, so that the horizontal axis is intercepted at 2°C (35.6°F) and 48°C (118.4°F). To determine the physiological indices the ordinates of the smoothed graph are measured for each degree of temperature considered; the numbers thus obtained represent the average hourly rate of elongation, in hundredths of a millimeter. Since it is often desirable to represent the growth rate as unity at 4.4°C (40°F), all hourly rates of elongation are divided by the value obtained at 4.4°C, or by 0.907, thus giving the physiological indices sought.

Livingston (8) presents a chart of the United States showing the climatic zones according to the physiological summation indices of temperature efficiency for the period of the average frostless season. This chart is presented in Fig. 37. The average growing season for Key West, Florida, is 365 days and shows a physiological summation index of 31,063 as compared to a growing season of 171 days and an index of 8,417 units at Des Moines, Iowa.

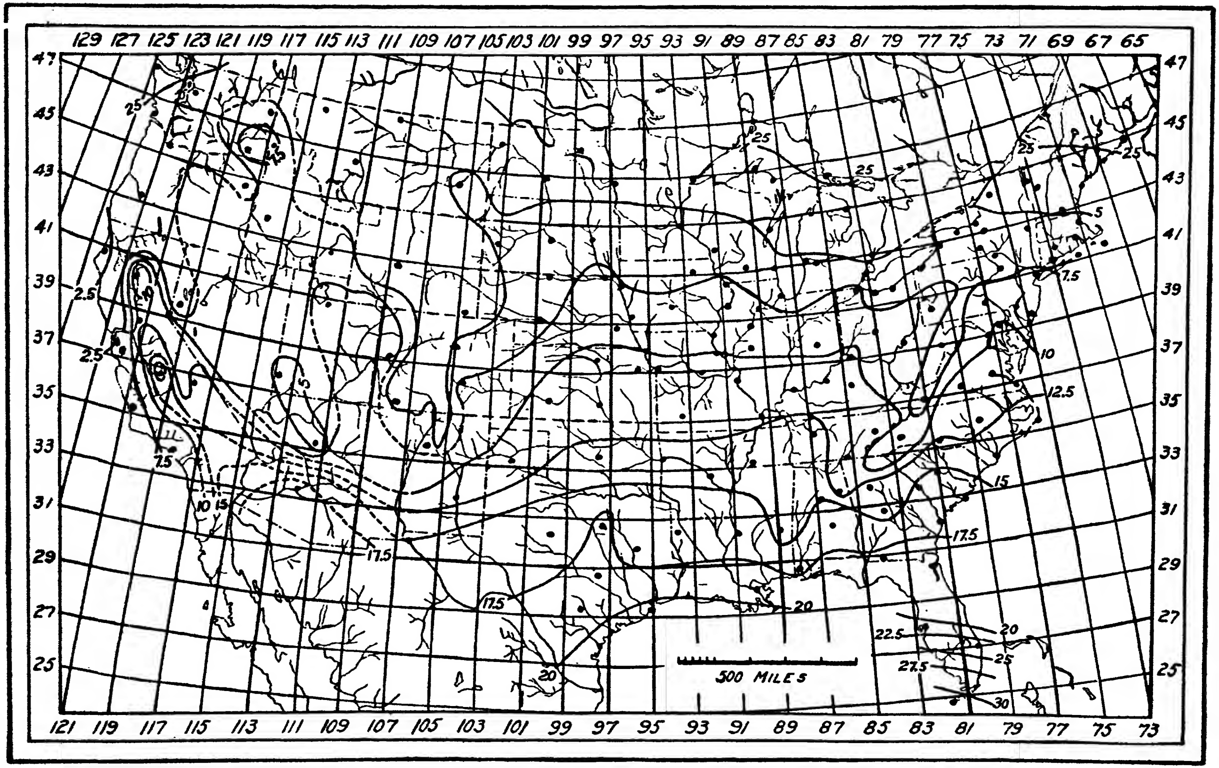


FIG. 37. Chart of the United States showing climatic zonation according to physiological summation indices of temperature efficiency for plant growth, for the period of the average frostless season. The numbers on the isoclimatic lines each represent thousands. Broken lines denote a very high degree of uncertainty. (After Livingston.)

Figure 38 shows the magnitude of the remainder, the exponential, and physiological temperature efficiency indices for increasing temperatures from 0 to 48°C, also Lehenbauer's graph of the relation of temperature to the rate of elongation of the shoots of maize

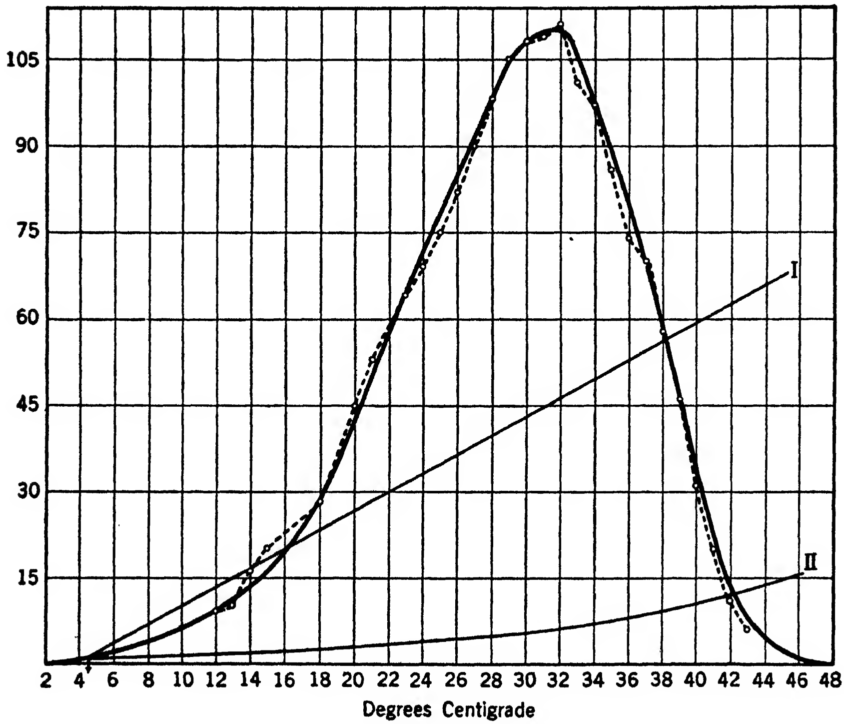


Fig. 38. Graphs showing increase in value of index of temperature efficiency for plant growth (ordinates) with rise in temperature itself (abscissas), for the three systems of indices. Graph I represents the remainder system, graph II, the exponential one. The broken line is Lehenbauer's graph of the relation of temperature to the rate of elongation of the shoots of maize seedlings. The smoothed graph corresponding to the latter represents the physiological system of indices. All graphs pass through unity at 4.5°C. (After Livingston.)

seedlings. The figure brings out the essential differences between the three above-indicated temperature efficiency indices.

The relative merits of the remainder, exponential, and physiological indices are discussed by Livingston (8) in the following paragraph.

"Whenever some of the temperatures dealt with in ecological or physiological studies are above 32°C (89.6°F) this system of physiological indices for growth must give markedly different results from

those obtained with the remainder or exponential system. That natural shade temperatures above this critical point are infrequent in regions where ecology has been most studied, is apparently the reason why these two indefinitely increasing series have appeared so satisfactory in practical application, as in the cases presented by Livingston and Livingston. But for a general system of temperature interpretation with respect to plant growth the physiological indices are sure to be preferred to either of the other kinds."

Pearson (13 and 14), though calling attention to the limitations of the system of physiological indices, found a good correlation between the distribution of different forest types and physiological temperature efficiency summations for the months from May to September, inclusive, in the San Francisco Mountains of Arizona.

Limitations to the Employment of Physiological Summation Indices. The physiological indices present a clear concept of the behavior of the experimental plant, maize, to the particular environmental conditions maintained by Lehenbauer in his experiments on which the growth values are based. That they give theoretical values is not denied. Livingston (8) summarizes their limitations for practical ecological purposes in the following paragraph.

"While it is quite apparent that the system of physiological indices here described is far superior, in several respects, to the other systems heretofore suggested, it is equally clear that these indices are to be regarded as only a first approximation and that much more physiological study will be required before they may be taken as generally applicable. In the *first place*, they are based upon tests of only a single plant species, maize, and there are probably other plants (perhaps even other varieties of the same species) for which they are not even approximately true. *Second*, these indicies are derived from the growth of seedlings, and no doubt other phases of growth in the same plant may exhibit other relations between temperature and the rate of shoot elongation. *Third*, these indices refer to rates of shoot elongation, and there are many other processes involved in plant growth, which may require other indices for their proper interpretation in terms of temperature efficiency. *Fourth*, they apply strictly only under the moisture, light, and chemical conditions that prevailed in Lehenbauer's experiments; with more light or with a different light mixture, with different humidity conditions, or with different moisture or chemical surroundings about the roots, these same plants, in the same seedling phase, may exhibit very different values of the temperature efficiency indices. *Fifth, and finally*, plants in nature are never subject to any temperature

maintained for any considerable period of time, and these indices are derived from 12-hour exposures to maintained temperatures. As MacDougal has well emphasized, the indices really needed for the ecological and physiological interpretation of temperature must take account of the varying temperatures that are almost always encountered in nature."

The Moisture-Temperature or Hydrothermal Index. The fact that the activity of plants is not determined entirely by one factor of the environment to the exclusion of all others has been pointed out on several occasions. The three most evident factors of environment are temperature, moisture, and light conditions. Livingston (9) presents an index of moisture-temperature efficiency using the formula:

$$I_{mt} = I_t \frac{I_p}{I_e}$$

In the above formula, I_{mt} represents the moisture-temperature or hydrothermal index. I_t is the index of temperature efficiency evaluated on the basis of the physiological index. I_p and I_e represent the indices of precipitation intensity and atmospheric evaporating power, respectively corresponding to the summations of the rainfall and evaporation for the period considered. The formulation of the hydrothermal index is based on the assumption that plant growth increases proportionately to the value of the rainfall index, that it is retarded proportionally to the index of evaporation, and that the temperature index is correlated with the rates of activity manifested by the plants. All three of these indices are interrelated in their relations to plant activity. It is, however, hardly to be expected that they may call forth a response always directly proportional to their magnitude.

Livingston (9) gives a chart showing the magnitude of the hydrothermal indices for the various sections of the United States. This chart is presented as Fig. 39. The values for southern Florida amount to 23,000 units as compared to 6,000 for the northern Corn Belt area. The rapid decrease of the indices from the heart of the Corn Belt to the Great Plains area, especially in the southern portion of this area, is very noticeable.

Moisture-temperature indices bring out very interesting relationships. The hydrothermal index is subject, since it is based in part on the physiological index, to the same criticism as the latter. The

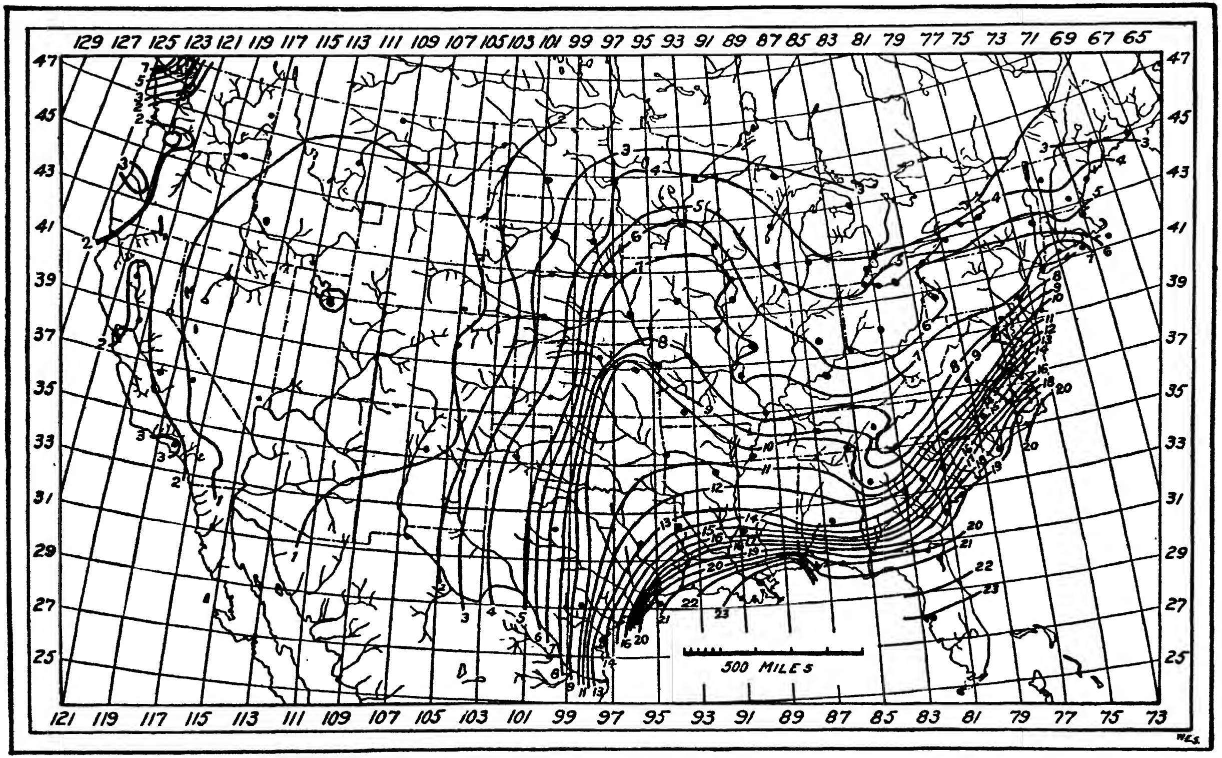


FIG. 39. Chart of the United States showing climatic zonation according to moisture-temperature indices of climatic efficiency for plant growth, for the period of the average frostless season. The numbers on the isoclimatic lines each represent thousands. (After Livingston.)

hydrothermal index makes no recognition of accumulation of supplies of moisture in the soil during the winter months which may play a very important part in the growth of plants after the beginning of the frostfree season.

CORRELATION OF DIFFERENT METHODS OF TEMPERATURE EFFICIENCY EVALUATIONS TO THE GENERAL DISTRIBUTION OF CROPS IN THE UNITED STATES

Interrelationship of Efficiency Indices. All of the temperature efficiency indices presented are more or less interrelated. Each has some particular advantage to recommend it, even if nothing more than simplicity; each also has some specific limitations either in actual determination or in broad application. Thornthwaite's temperature efficiency index amounts to nothing more than a modification of the remainder index. The length of the growing season enters into the summations of all of the various methods. It is not only a matter of interest, it is also of practical value, in studies relating to crop distributions, to ascertain the extent to which the various indices are actually interrelated. It is evident that the simpler indices may have a greater usefulness than the more complex ones if it can be demonstrated that a high degree of correlation exists between them. This may be true especially when the fundamental data required for calculating the more complex indices, such as the highly theoretical physiological and hydrothermal indices, are not available, or in locations where the application of these indices is not justifiable because of the indicated limitations to their utilization.

Magnitude of Indices in the Centers of Production of Specific Crops. Table 13 gives a comparison of the different methods of temperature evaluation in relation to the distribution of 16 cool- and 16 warm-weather crops in the United States. The various indices for the respective areas of production of each of the crops listed were taken from the data presented by Livingston. In most instances the values given for some station located in the center of most intensive production for each respective crop could be utilized. In a few instances where the particular center of production of some crop was not represented by a station in Livingston's data, it was necessary to make use of general values for the region of

TABLE 13. THE MAGNITUDE OF VARIOUS TEMPERATURE EFFICIENCY INDICES IN THE AREAS OF MOST INTENSIVE PRODUCTION OF 16 COOL- AND 16 WARM-WEATHER CROPS IN THE UNITED STATES

Crop	Center of Production Selected	Frost-Free Season, in Days	Temp. Summation or Remainder Index	Temp. Efficiency or Exponential Index	Physiological Index	Hydrothermal Index
Cool-weather crops						
Flax	Moorhead, Minn.	132	3,351	334	4,283	4,043
Potatoes	Green Bay, Wisc.	153	3,696	382	4,942	4,270
Rye	Devils Lake, N. D.	121	2,939	301	3,754	2,823
Barley (spring) . . .	Moorhead, Minn.	132	3,351	334	4,283	4,043
Sugar beets	Saginaw, Mich.	140	3,700	360	4,500	4,300
Hard red spring wheat	Devils Lake, N. D.	121	2,939	301	3,754	2,823
Soft red winter wheat .	Indianapolis, Ind.	186	5,341	467	9,441	5,967
Durum wheat . . .	Devils Lake, N. D.	121	2,939	301	3,754	2,823
Oats (spring) . . .	Charles City, Iowa	133	4,000	403	6,630	7,000
Hard red winter wheat	Central Kansas	170	5,500	475	10,500	7,000
Field beans	Lansing, Mich.	145	4,000	400	5,000	4,000
Field peas	Green Bay, Wisc.	153	3,695	382	4,942	4,270
Buckwheat	Ithaca, N. Y.	160	4,017	440	5,659	5,000
Timothy hay . . .	Buffalo, N. Y.	173	3,666	491	5,761	4,511
Soybeans	Springfield, Ill.	182	5,344	563	9,464	7,032
Corn (northern) . .	Yankton, S. D.	154	4,464	464	7,616	6,491
Means		148.5	3,996.4	406.1	5,892.7	4,774.8
Warm-weather crops						
Cotton (eastern) . .	Vicksburg, Miss.	252	8,204	893	16,194	15,125
Cotton (western) . .	Fort Worth, Tex.	261	8,637	961	17,652	15,200
Corn (southern) . .	Springfield, Ill.	182	5,344	563	9,464	7,032
Tobacco	Raleigh, N. C.	213	7,584	700	12,329	14,980
Oats (winter) . . .	Fort Worth, Tex.	261	8,637	961	17,652	15,200
Barley (winter) . .	Charlotte, N. C.	220	6,736	718	12,552	11,022
Grain sorghums . .	Amarillo, Tex.	199	5,781	599	10,668	4,673
Broom corn	Panhandle of Okla.	187	5,800	600	11,000	5,000
Peanuts	Macon, Ga.	238	7,549	810	14,564	14,000
Velvet beans . . .	Macon, Ga.	238	7,549	810	14,564	14,000
Bermuda grass . . .	Montgomery, Ala.	243	8,141	886	16,511	12,400
Sugar cane	New Orleans, La.	310	9,881	1,077	19,323	23,381
Early potatoes . . .	Jacksonville, Fla.	293	9,339	1,033	18,791	21,760
Sweet potatoes . . .	Montgomery, Ala.	243	8,141	886	16,511	12,400
Cowpeas	Raleigh, N. C.	213	7,584	700	12,329	14,980
Rice	Lake Charles, La.	260	9,800	1,000	17,750	20,000
Means		238.3	7,794.2	824.8	14,865.9	13,822.1

intensive production of that crop. It will be observed that the length of the growing season, as well as the values of the various

temperature indices, such as the remainder, exponential, physiological, and hydrothermal, are in most instances significantly lower for the cool- than for the warm-weather crops. The difference in the temperature requirements for each of the groups of crops is especially well brought out by a comparison of the means for the cool- and the warm-weather crops. The line of demarcation between these two groups of crops is of necessity somewhat arbitrary.

It is necessary to call attention to one factor in particular that should be kept in mind in interpreting the data presented in Table 13 and in the correlation studies which follow, namely, that some of the crops grown in both the northern and southern portions of the United States do not make full use of the entire growing season while the temperature indices are based on the accumulations of values for the entire length of the frostfree period of the year. The most outstanding examples of this are in evidence in the production of early white potatoes in the southern states, and to a lesser degree in the production of the cereals both in the North and in the South. The classification of cool- and warm-weather crops as used here refers more especially to the temperature provinces of the areas of production of the given crops rather than to the temperature conditions prevailing during their respective vegetation rhythms.

Correlation of Magnitude of Temperature Efficiency Indices to Crop Distribution. Table 14 gives the values of the coefficient *r* obtained from multiple correlations of the values of temperature efficiency indices prevailing in the different areas of most intensive production of important crops in the United States. Two sets of supporting correlation data are presented. One, the original study, is based on the distribution of eight cool- and eight warm-weather crops in which the magnitudes of the different temperature indices were taken for the general regions of intensive production of each crop. The second is based on the data presented in Table 13. The values of *r* obtained from these two sets of data are remarkably alike.

The length of the average frostfree season shows a high and very significant degree of correlation with the other four indices. The correlations between the various temperature indices are also high. The values of *r* are in all instances sufficiently high to be used for purposes of prediction. The high values for the remainder and exponential indices are to be expected. It is interesting to note the high values of *r* obtained between the length of the average frostfree

season and the more complex physiological and hydrothermal indices as well as the high values between the remainder and exponential, and the physiological and hydrothermal indices. It must be kept in mind that the physiological index enters definitely into the actual calculation of the hydrothermal index.

TABLE 14. VALUES OF r IN TWO SETS OF MULTIPLE CORRELATIONS OF FIVE DIFFERENT METHODS OF EVALUATING EFFECTIVE TEMPERATURES BASED ON THE INDICES PREVAILING IN THE AREAS OF MOST INTENSIVE PRODUCTION OF EIGHT COOL- AND EIGHT WARM-WEATHER, AND 16 COOL- AND 16 WARM-WEATHER CROPS IN THE UNITED STATES OF EACH OF THE RESPECTIVE CROPS

Methods of Evaluating Effective Temperatures	*Remainder Index*	*Exponential Index*	*Physiological Index*	*Hydrothermal Index*
Eight cool- and eight warm-weather crops — based on regional values				
Length of frostfree season	0.984 ± 0.006	0.981 ± 0.007	0.977 ± 0.008	0.958 ± 0.014
Remainder index .	—	0.990 ± 0.003	0.974 ± 0.009	0.944 ± 0.019
Exponential index .	—	—	0.979 ± 0.007	0.948 ± 0.018
Physiological index .	—	—	—	0.933 ± 0.023
16 cool- and 16 warm-weather crops — based on data of specified stations				
Length of frostfree season	0.980 ± 0.005	0.991 ± 0.002	0.976 ± 0.006	0.933 ± 0.015
Remainder index .	—	0.995 ± 0.001	0.987 ± 0.003	0.949 ± 0.012
Exponential index .	—	—	0.988 ± 0.003	0.936 ± 0.015
Physiological index .	—	—	—	0.919 ± 0.018

Livingston (8) gives data relative to the length of the average frostfree season and the corresponding calculations of the physiological summation indices for 170 stations in the United States. The correlations of these data are indicated in Fig. 40. The coefficient of correlation between the length of the growing season and the physiological index for each of the 170 stations representing all 48 states shows a value of 0.739 ± 0.025. When 15 of the stations to which the system of physiological summation indices obviously do not apply are eliminated from the calculation, the value of r for the data of the remaining 155 stations becomes 0.950 ± 0.005. The stations eliminated in the second calculation of the relationship between the two factors are indicated in Fig. 40. It will be observed that all of these stations have climates influenced by marine locations. Corn is not adapted to marine types of climates

with relatively long but cool growing seasons. Since the calculation of the physiological index is based on the temperature response of corn, there is ample justification for the elimination from the correlation studies of these marine stations, or stations located in sections with relatively long but cool growing seasons such as represented by Spokane, Washington.

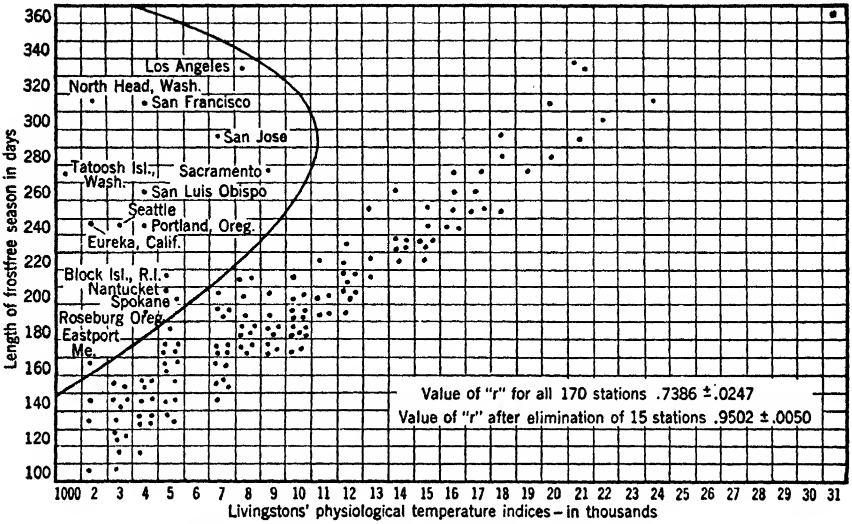


FIG. 40. Correlation of Livingston's physiological temperature efficiency indices and length of average frostfree season for 170 stations of the United States. Correlations are presented for all stations for which data are available and for 155 stations after the elimination of 15 indicated stations to which the physiological indices obviously do not apply.

The close relationship between the length of the growing season and the hydrothermal index is brought out in Fig. 41, showing the correlation of the average length of the frostfree season and the calculated hydrothermal index for each of the 112 stations of the United States, given by Livingston (9). The value of r for all 112 stations is 0.629 ± 0.041. When 12 of these stations are eliminated from the calculation, for the same reason as given for the elimination of stations in the correlation of length of growing season and the physiological index summations, the value of r for the remaining 100 stations is increased to 0.873 ± 0.015. The stations eliminated are indicated in Fig. 41. The hydrothermal index fails to give a true value for such sections where a high percentage of the annual

precipitation falls during the winter months and where conditions are favorable to the penetration and later utilization of such moisture. Additional stations, notably those in irrigated areas, could be eliminated from the second correlation and result in a material increase in the value of *r*. Thus the lengths of the average frostfree seasons as given by Livingston are identical for Boise, Idaho, and

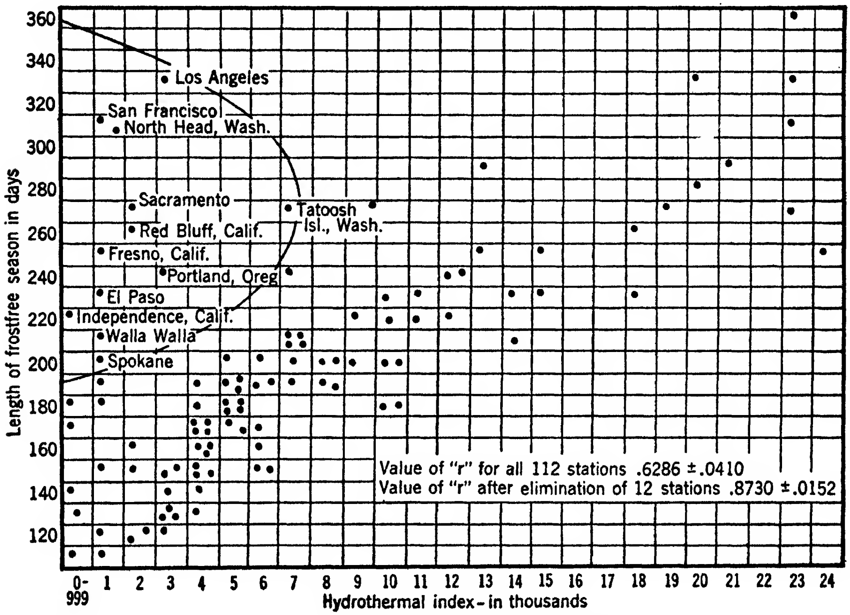


FIG. 41. Correlation of Livingston's hydrothermal efficiency indices and the length of the average frostfree season for 112 stations in the United States. Correlations are presented for all stations for which data are available and for 100 stations after the elimination of 12 indicated stations to which the hydrothermal indices obviously do not apply.

for Albany, New York, namely, 177 days. The hydrothermal index for the former is given as 598 and for the latter as 5,598 units. Since natural precipitation in the Boise Valley is supplemented by irrigation, not infrequently to the extent of several times the amount of the rainfall during the growing season, the differences in the hydrothermal indices for the irrigated section in Idaho and the humid New York station give no index of the relative crop producing capacities of the two areas.

The employment of the length of the growing season as an index of effective temperatures for a given locality has definite limitations

even though high degrees of correlations were demonstrated between it and the more theoretically firmly grounded and complex indices discussed. On the other hand the evaluation of effective temperatures for any locality must always be undertaken in connection with the temperature requirements and responses of the particular crop to be grown regardless of what method of evaluation may be selected.

The establishment of Thornthwaite's temperature provinces on a linear basis of evaluating temperature efficiencies has been criticized from the standpoint of the utilization of the remainder index in an empirical form. The close correlations here reported between the length of the growing season and the various other theoretically better fortified methods of evaluating effective temperatures indicates that either the length of the frostfree season or the also readily calculated remainder index can be used to advantage in the establishment of temperature provinces and for purposes of general climatic classification.

BIOCLIMATICS

Temperature Zones. Bioclimatics as defined by Hopkins (5) is the "science of relations between life, climate, seasons, and geographical distribution." The sun is the primordial cause of all bioclimatic phenomena. The rotation of the earth around the sun accounts for the alteration of light and darkness with its regular climatic, and especially temperature changes. The inclination of the earth on its axis causes the variations in seasons and the major climates, and again the most outstanding phenomenon is temperature and with it differences in length of days.

Astronomically, three broad temperature zones — the torrid, temperate, and frigid — are recognized in latitudinal belts around the world. The torrid zone is bounded to the north by the Tropic of Cancer and to the south by the Tropic of Capricorn, situated on each side of the equator at a distance of 23°28′ and parallel to it. These two lines represent the points reached by the sun at its greatest declination north or south, from which it turns again to the equator. There are, of course, two temperate zones lying between either tropic and the corresponding polar circle, and two frigid zones.

Henry *et al.* (3) give five temperature belts in relation to plant life. The main characteristics of each belt are listed as follows:

1. The tropical belt, regions of the megatherms, with all months warm; that is, the temperature averaging over 68°F.
2. The subtropical belts, with 4 to 11 months warm, averaging over 69°F. The plants are largely megatherms.
3. The temperate belts, regions of the mesotherms, with 4 to 12 months of moderate temperature of 50 to 68°F.
4. The cold belts, regions of the microtherms, with 1 to 4 months temperate, and the rest cold, below 50°F.
5. The polar belts, regions of the hekistotherms, with all months averaging below 50°F.

Astronomical and Isothermal Temperate Zones. A glance at Fig. 42 shows that the isotherms, lines connecting points of equal temperature, follow the astronomical zones in a general manner only. The astronomical zones are defined strictly by parallels of latitude; they do not take into consideration the temperature deviations caused by oceanic and continental influences. Supan

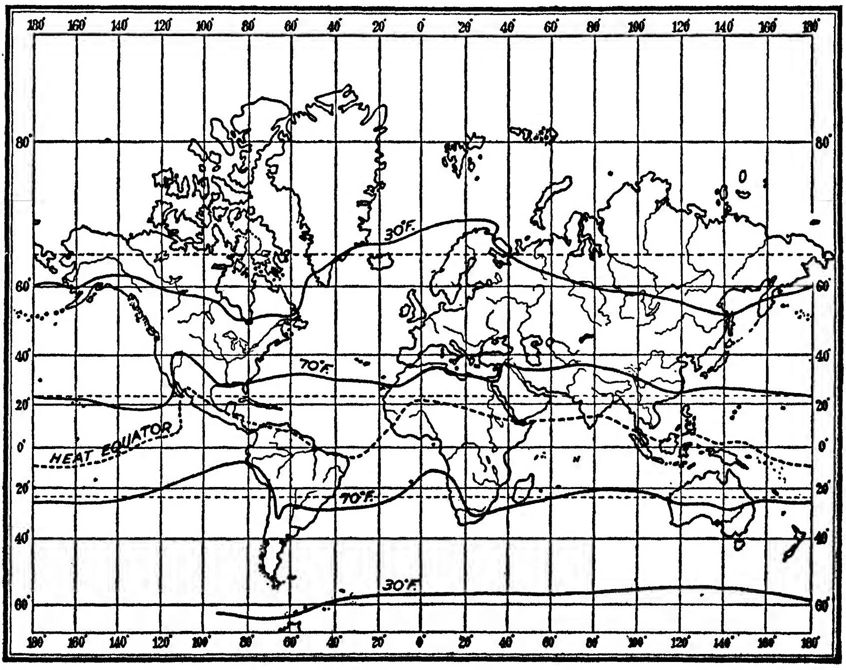


FIG. 42. Mean annual isotherms for 70 and 30°F north and south, and the heat equator of the world. (After Hopkins.)

(16) based his temperature zones on sea-level isotherms. He recognized three general zones; the hot belt, bounded on the north and south by the isotherms representing the mean annual temperature of 20°C (68°F); the temperate belts lying between these lines and the isotherm of 10°C (50°F) for the warmest months; and the cold caps, extending from the regions around the poles to the isotherm 10°C for the warmest months. The polar boundaries of agriculture are not far from the annual isotherms of 30°F.

Bioclimatic Zones. Hopkins established bioclimatic zones on the basis of his bioclimatic law promulgated to take into consideration the effects of oceanic, continental, and physiographical features on temperature and life zones in general. The bioclimatic law as stated by Hopkins requires

> "that across the continents under equal physiographic conditions the phenomena of the seasons, climate, and life should be equal at the same level along lines designated as isophanes, which depart from the parallels of latitude at the rate of 1° of latitude to 5° of longitude; and that, with distance in degrees of latitude poleward and equatorward from such a line, or in feet of altitude above or below a given level, the required effects should vary at a uniform constant rate as measured in units of time or temperature."

The time coordinate for the occurrence of a given periodic event in plant activity, such as first date of flowering, or maturity of a given plant, is stated by Hopkins to be at the general average rate of four days to each degree of latitude and 400 feet of altitude from a given point later northward in spring and early summer. The effects of degrees of longitude are explained in the position of the isophanal lines in relation to the parallels of latitude. The thermal coordinates are 1°F for each degree of latitude, each 5° of longitude, and for each difference of 400 feet in elevation.

The above will become clear upon an examination of the isophanal map of the world, Fig. 43. Hopkins presents more detailed maps of each of the continents, and sea-level isophanal zones of the continents and oceans. His isophanal map of the world will suffice for the discussion here. The isophanes are shown in straight lines at intervals of 20° of latitude to 100° of longitude as unbroken lines across the continents and broken lines across the oceans.

> "It will be noted," states Hopkins, "that, while the numerical designations are the same on the one hundredth meridian east or west,

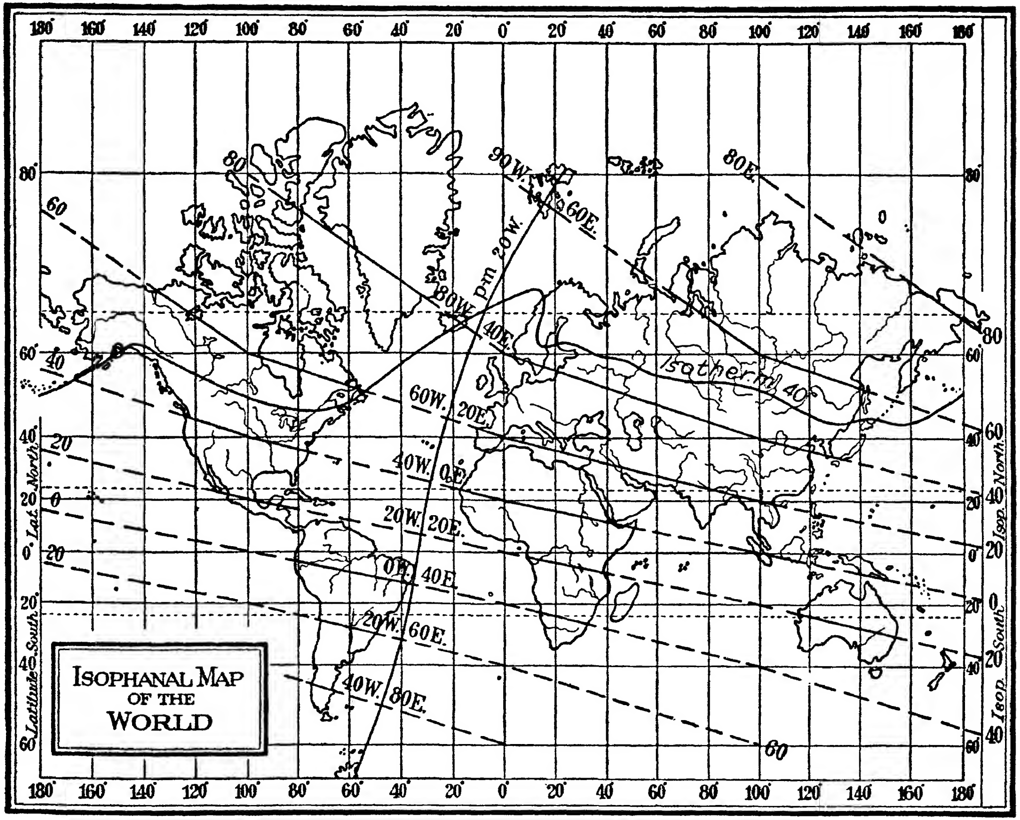


Fig. 43. Isophanal map of the world, with isotherm 40°F. (After Hopkins.)

> there is a difference of 40° on pheno-meridian 20 W between those for the Eastern and Western Hemispheres. This is due to the southeast trend of the western and northwest trend of the eastern isophanes of the same numerical designation from the one hundredth meridians (west and east) to the Atlantic coast. Thus if the isophanes of the same number were connected across the Atlantic Ocean, isophane 40, *e.g.*, would appear as a line whose southwestward trend across the Atlantic corresponds in general with that of the mean annual 40°F isotherm. There is also a general agreement in the trend of the 40° isotherm and the fortieth isophane across North America and Eurasia."

The isophanes as indicated in Fig. 43 apply only to land areas. The respective isophanal lines are numbered to correspond with the parallels of latitude intersected by them on the one hundredth meridian of longitude west and east of Greenwich. Thus isophane 40 W intersects the one hundredth meridian west of Greenwich on the latitude 40° North, that is, on the western portion of the border line between Kansas and Nebraska. Likewise, isophane 40 E intersects the one hundredth meridian east of Greenwich on the latitude 40° North, in central China.

The isophanal and bioclimatic maps and data presented by Hopkins are of value for the rapid general comparisons of life phenomena of distant areas. In that respect they may become of definite value to the study of crop distribution. As stated by Hopkins,

> "while this system of continental isophanes represents the requirements of the bioclimatic law, as related to any sea level or any common level across the terrestrial areas alone, and while the parallels of latitude represent equal phenomena and apply to both land and water, it is found that lines of equal effect in phenomena of life and climate correspond in their trend with the isophanes rather than with the parallels of latitude."

Evans (2) presents data from his studies of the relation of latitude to the time of blooming of timothy to the effect that Hopkins' bioclimatic law does not give proper emphasis to the gradually increasing length of day, from southern to northern latitudes. The season of blooming of timothy at a series of stations extending from Savannah, Georgia, to Fairbanks, Alaska, progressed at constantly accelerated rates rather than at a uniform constant rate according to the bioclimatic law. This indicates that "other varying factors in addition to those of latitude, longitude, and altitude, must be considered" in bioclimatic relationships.

Merriam's Life Zones and Areas. While the life zones recommended by Merriam (12) are at present mainly of historical interest, it must be recognized that his classification of the life zones of the United States and North America gave a real impetus to the study of the effects of temperature and rainfall and to the establishment of biothermal lines and of the factors determining the distribution of plants and animals.

Merriam recognized two great lines of stress, heat and rainfall, as influencing the limits of migration of species in the higher latitudes and at higher elevations. Likewise, excessive heat constitutes one of the main contributing factors limiting the growth of many plants in the lower latitudes. He evaluated heat by the summation of mean daily temperatures above 6°C (43°F) from the time growth begins in spring to the time growth ceases in fall, that is, by the remainder index. Differences in rainfall constitute the second line of stress. It should be noted that Merriam used total rainfall rather than a system of precipitation efficiency.

Three transcontinental life regions are recognized in the northern hemisphere: the Boreal, or northern; the Austral, or southern; and the Tropical. These regions were first established by Alexander von Humboldt when he divided the globe into the great life belts. Humboldt, however, used isothermal lines rather than temperature summations as did Merriam.

The Boreal region covers the whole of the northern part of North America, from the Polar Sea southward to near the northern boundary of the United States, and farther south occupies a narrow strip along the Pacific coast and the higher parts of the three great mountain systems, the Sierra Cascade Range, the Rocky Mountains, and the Alleghanies. The Boreal region is subdivided, along the lines of stress due to heat, into three zones, the Arctic or Arctic-Alpine, the Hudsonian, and the Canadian. The Arctic or Arctic-Alpine zone is the northernmost and highest belt; it lies beyond the limit of tree growth, and the larger part of it is perpetually covered with snow and ice. The Hudsonian, or subarctic zone, embraces the most northern part of the great transcontinental coniferous forests. Because of low temperatures it is of no agricultural importance. The Canadian zone comprises the southern part of the great transcontinental coniferous forest of Canada and the very northern portion of the United States. Favored locations along

the southern border of this belt are suited to the production of potatoes, hardy vegetables, and cereals.

The Austral region covers the whole of the United States and Mexico, except the Boreal mountain heights and the tropical lowlands. It is divided, along lines of stress due to heat, into the Transition, Upper Austral, and Lower Austral zones. Each of these zones is subdivided into areas along lines of stress due to rainfall and drought. Thus the Transition zone, the meeting place of the boreal and austral types, located in the northern portion of the United States, is broken up into the Humid Alleghanian, Arid Transition, and Pacific Coast Transition areas. The Upper Austral zone is divided into an eastern humid, or Carolinian area, and a western arid or Upper Sonoran area. The Lower Austral zone occupies the southern part of the United States. It, likewise, is broken up into an eastern, or Austroriparian, and a western, or Lower Sonoran, area.

The Tropical region has no stress lines due to heat, but is divided into humid and arid areas.

REFERENCES

1. Cohen, E., *Lectures on Physiological Chemistry for Physicians and Biologists,* trans. German by Martin H. Fisher. New York, 1902.
2. Evans, M. W., "Relation of latitude to time of blooming of timothy," *Ecology,* 12:182–187 (1931).
3. Henry, A. J., J. B. Kincer, H. C. Frankenfield, B. B. Smith, and E. N. Munns, "Weather and agriculture," *U. S. Dept. Agr. Yearbook* 1924: 457–558.
4. Hertwig, O., "Über den Einfluss der Temperatur auf die Entwicklung *Rana fusca* und *Rana esculenta,*" *Arch. f. Microscop. Anat. und Entwicklungsgesch.,* 51:318–381 (1898).
5. Hopkins, A. D., "Bioclimatics, a science of life and climate relations," *U. S. Dept. Agr. Misc. Pub.* 280, 1938.
6. Kincer, J. B., "The relation of climate to the geographical distribution of crops in the United States," *Ecology,* 3:127–133 (1922).
7. Lehenbauer, P. A., "Growth of maize seedlings in relation to temperature," *Phys. Res.,* 1:247–288 (1914).
8. Livingston, B. E., "Physiological temperature indices for the study of plant growth in relation to climatic conditions," *Phys. Res.,* 1:399–420 (1916).

9. Livingston, B. E., "A single index to represent both moisture and temperature conditions as related to plants," *Phys. Res.*, 1:421–440 (1916).
10. ———, and Grace J. Livingston, Temperature coefficients in plant geography and climatology," *Bot. Gaz.*, 56:349–375 (1913).
11. Matthaei, G. L. C., "Experimental researches on vegetable assimilation and respiration, III, On the effect of temperature on carbon dioxide assimilation," *Phil. Trans. Roy. Soc. London*, 197:47–105 (1904).
12. Merriam, C. H., "Laws of temperature control of the geographic distribution of terrestrial animals and plants," *Nat'l Geog. Mag.*, 6:229–238 (1894).
13. Pearson, G. A., "Temperature summations with reference to plant life," *Mo. Wea. Rev.*, 52:218–220 (1924).
14. ———, "Forest types in the southwest as determined by climate and soil," *U. S. Dept. Agr. Tech. Bull.* 247, 1931.
15. Seeley, D. A., "Relation between temperature and crops," *Mo. Wea. Rev.*, 45:354–359 (1917).
16. Supan, A., *Grundzüge der physischen Erdkunde.* Aufl. 3, Leipzig, 1903.
17. Thornthwaite, C. W., "The climates of North America according to a new classification," *Geog. Rev.*, 26:633–655 (1931).

Chapter XVIII

LIGHT

GENERAL ASPECTS

Light in Relation to Growth Requirements and as a Factor in Geographical Distribution. Schimper (21) designates light as, next to moisture, the most important environmental factor determining the structure of plants. Both water and light provide actual materials essential to the building up of the structures of higher plants, while temperature, as has been pointed out, provides the necessary working condition.

Schimper proceeds then to point out that the light factor is of less importance than the water and temperature factors as it relates to the geographical distribution of plants, notwithstanding its prime importance to nutritional and structural effects. This is because the differences in both the quantity and quality of light in relation to the needs of plants are not so pronounced in different climatic regions as are differences in the moisture and temperature factors. This is well brought out by Raunkiaer (20) in the following paragraph.

> "The requirements for the life of plants are all of equal importance inasmuch as none of them can be dispensed with; but when these requirements are used as a foundation for dividing up the earth into equiconditional regions they are very far from being of equal importance. Some, for example the amount of oxygen and carbon dioxide in the air, differ so little in different places that they have no significance for the life forms, and therefore cannot be used as characters for equiconditional regions. Others, for example the chemical and physical nature of the soil, the relationship between plants and animals, and between plants themselves, vary so widely even within the smallest districts that they cannot be used for limiting large equiconditional regions; but on the other hand they are useful in the detailed analysis of vegetation within these regions. The same is approximately true of light. If the demand for light always expressed itself sufficiently obviously in the structure of plants, and if the plants were all of equal

height and shaded each other equally, then the different intensity of sunlight in the different degrees of latitude would be an important factor for limiting large equiconditional areas. But there is a vast difference in the size of plants, and some grow in the shade of others, so the relationship of light even in very small areas differs so greatly that it is impossible to use it for determining what is common to the environment over extensive tracts."

The Heating and Chemical Effects of Light. The sun is the source of both heat and light. Furthermore, heat and light are definitely associated. Two units are therefore employed in measuring the intensity of sunlight, one a heat and the other a light unit. The gram-calorie, the quantity of heat required to raise the temperature of a gram of water through 1°C, is the unit usually employed for measuring total radiant energy, that is, the energy of all wave lengths received from the sun. The foot-candle is the unit used for measuring brightness, or the wave lengths capable of producing the sensation in the human eye commonly referred to as light. According to Henry *et al.* (12), the intensity of solar or daylight illumination on a horizontal surface around noon in midsummer is with a clear sky about 10,000 foot-candles. The intensity may still be between 2,500 to 3,000 foot-candles when the sky is completely covered with clouds. An intensity of from 10 to 15 foot-candles is considered good indoor illumination.

The shorter waves of the spectrum have primarily chemical effects, either detrimental or conducive to photosynthesis, while the longer waves produce mainly temperature effects. Wave lengths in excess of 0.76 micron have primarily temperature effects; those shorter than 0.40 micron have decided detrimental effects on the chlorophyll of higher plants. A micron is a thousandth part of one millimeter.

Interrelationship of Environmental Factors. That the effects of light on plants and crop plants in particular must be considered in relationship with other factors of the environment is obvious. Under most conditions the quantity of light present is sufficient for the normal requirements of crop plants. Since light intensity and duration are associated with temperature, the responses called forth by a high intensity of light not infrequently amount to temperature responses. Furthermore, the actual amount of radiant energy which may be utilized by plants is highly dependent on

other factors of the environment either favorable or unfavorable to the establishment or maintenance of a proper physiological balance. Thus a plant well supplied with moisture and the necessary nutrients is able to utilize more radiant energy than one growing in an unfavorable environment. Under some conditions a high intensity of light may be detrimental not only because of its direct destructive effects on the chlorophyll but more frequently because of its indirect and associated temperature effects; the intensifying of destructive processes may in such cases be attributed to a greater extent to the temperature than to the light factor. Drought damage usually occurs under conditions of high intensity and duration of light, high temperatures, and the associated low atmospheric humidity. All three of these conditions usually conspire to form the formidable trio demanding increased expenditures of the little remaining water available to drought-stricken plants.

The Action of Light on Plants. The action of light on plants has many important and interesting physiological ramifications entirely beyond the scope of this chapter. All that can be given here is a brief summary taken directly from Warming (27). The part played by light is presented in the following eight points:

"1. *By its chemical action on chlorophyll.* Without light there would be no production of chlorophyll, no assimilation of carbon dioxide, and no life upon the globe.

2. *By its heating action.*

3. *By promoting transpiration through rise of temperature.*

4. *By promoting growth movements*, the position of foliage-leaves, and nearly all vital phenomena.

5. *By influencing the distribution of plants.*

6. *The development of plants* depends not only upon the intensity but also upon the duration of the light to which they are exposed.

7. *Direct light promotes the production of leaves and flowers.*

8. *The vegetative shapes of plants* are greatly influenced by the intensity and direction of the light."

QUALITY OF LIGHT

Differential Effects of the Rays of the Spectrum. Sunlight is variable in quantity, duration, and quality. The term "quality" of light is used here in reference to the composition of light in relation to its effects on plants. When a beam of light is dispersed by refraction through a prism the rays arrange themselves in a

series according to their wave lengths. Thus the composition of light may be analyzed as to the rays it contains. The relationship of these rays to plant behavior and to the question of optimum intensities of light is pointed out by MacDougal (16) in the following paragraph.

> "Not all of the rays of the spectrum are concerned in the various influences exerted by light upon living matter, but only waves of certain wave-lengths are active in each. It is not possible therefore to fix upon a minimum, optimum, and maximum intensity of light which is common to all of the relations between the plant and light."

Lundegårdh (15) presents a tabulation showing the effects of different wave lengths of light on plant life. This is presented as Table 15.

TABLE 15. THE ACTION OF DIFFERENT RAYS OF RADIANT ENERGY ON PLANT LIFE (after Lundegårdh)

Rays	*Wave Lengths*	*Effects on Plants*
Röntgen	0.00001–0.000018 micron	Decidedly very detrimental
Ultraviolet	0.042–0.40 micron	Very detrimental
Violet, Blue	0.40–0.49 micron	Phototropism. Photomorphosis
Green-red	0.49–0.76 micron	Carbon-dioxide assimilation
Ultrared	0.76 to around 600 microns	Temperature factor in general
Electric waves	2 mm. to indefinite length	Unknown

Lundegårdh points out that a distinct differentiation between the actions of the various rays is usually not possible. All rays that are physically absorbed exert a certain temperature effect. Yellow and red rays are also active in phototropism but to a much smaller degree than blue-violet rays. It is recommended that for ordinary ecological purposes it is sufficient to evaluate the blue-violet and the yellow-red rays in addition to the total intensity.

Shirley (24) considers the measurement of separate rays of secondary importance to the evaluation of the total light intensity. "The entire visible and ultra-violet solar spectrum is more efficient for the growth of the plants studied than any portion of it used; the blue region is more efficient than the red region."

Effects of Atmospheric Conditions on Quality of Light. The exact composition of light coming in contact with plants is highly

dependent on atmospheric conditions but especially on the amounts of moisture and dust in the air. Pulling (19) points out seven ways by which losses from incoming solar energy occur.

1. General scattering by the permanent gases of the atmosphere.
2. General scattering by water vapor.
3. Selective (banded) absorption by permanent gases.
4. Selective (banded) absorption by water vapor.
5. Absorption and reflection by clouds.
6. Absorption and reflection by dust particles.
7. Absorption in chemical reactions.

According to Dorno, cited by Lundegårdh, the short-wave rays are influenced to a greater extent than the long-wave rays by the presence of clouds.

Altitude and Composition of Sunlight. Since the atmospheric strata become less dense with increasing elevation above sea level, it is evident that there is less absorption of radiant energy at high than at low altitudes. Hann (10) points out that the rapid increase in the intensity of solar radiation with increase in altitude is largely attributable to the decrease and almost total absence of atmospheric dust (including under this term aqueous condensation products) which affects chiefly the shorter waves. Consequently these are especially strong at high elevations. The diminution of water vapor also plays a part in this, though not so pronounced a part as the decrease in atmospheric dust.

The most outstanding difference in the composition of light at low and high elevations is the marked increase in the intensity of the ultraviolet rays. Anyone not accustomed to exposure to the direct rays of the sun will develop a good tan or even a severe sunburn at great altitudes.

That the great intensity of solar radiation, and especially the intensity of the ultraviolet rays, has a great influence on the characteristics of Alpine plants has been pointed out by numerous investigators. Thus Alpine plants are characterized by short internodes, firm leaves, more or less wrinkled surfaces, and a dark color.

Seasonal Variations in the Composition of Sunlight. It has been pointed out that the composition of sunlight is affected by a variety of atmospheric factors. There is also a significant change in composition as the season advances. This is brought out graphi-

cally by Dorno in Fig. 44, taken from Lundegårdh's book. According to Lundegårdh, while the heat rays at noon increase but by 10 per cent from winter to summer, the red rays increase by 45, the light rays by 60, the green rays by 90, the blue-violet rays by around 1,000 per cent.

A study of Fig. 44 reveals that sunlight in summer and also during the autumn months contains a higher proportion of the chemically active rays, that is, a relatively greater predominance of the ultraviolet and blue-violet rays, than in winter or during the spring months.

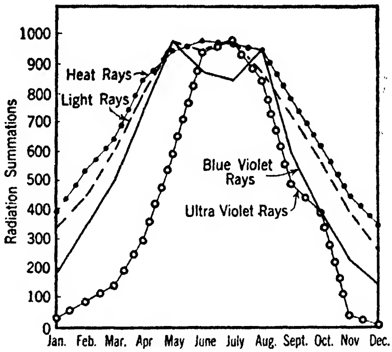


Fig. 44. Variations in the composition of sunlight at the fifteenth day of the indicated months throughout the year. (After Dorno, taken from Lundegårdh.)

From the standpoint of plant activity the greater length of the days in spring and summer is of great importance. This factor will be treated in detail later.

QUANTITY OF LIGHT

General Dependence of Plants on Quantity of Light. Under ordinary conditions of field crop production a sufficient total amount of light for the normal growth of plants is available. Generally crop plants do best when grown under full sunlight, provided that such exposure does not, by the heating action of light, cause other factors of the environment to drop below the minimum requirements for growth. Blackman and Matthaei (3) and others have shown that the rate of photosynthesis with low light intensities is almost directly proportional to the light intensity if other factors are not limiting. At higher intensities, the slope of the curve showing production of dry weight falls off and approaches according to Boysen-Jensen (4), and Harder (11), a line parallel to the axis. Shirley reports that the dry weights of plants studied by him increased almost in direct proportion to the light intensity received up to about 20 per cent of full summer sunlight. At higher intensities the slope of the curve fell off, with shade plants showing a decrease at lower intensities than sun plants.

Tippett (25), working at Rothamsted on the effects of sunshine on wheat yields, presents data showing that sunshine seems to have a large positive effect in autumn and winter. It has less effect on yields in the spring and again a more decided effect in the summer months "primarily because of its aid to development and ripening of the grain." The effects during the summer months were not, however, as great as during the autumn and winter months when sunshine with the associated slight changes in soil temperature had favorable effects on the root development of plants.

In humid areas cloudiness may at times be enough, if continuing over a sufficiently long period, to slow down the growth rate of plants. Usually, however, this is not the case. Plants are able under most conditions to develop quite normally with less than full sunlight. In continental climates and especially during times when moisture is lacking, exposure to full sunlight is decidedly detrimental as it materially increases the demand for and the actual loss of water from plants and from the soil. Periods with overcast skies and lower temperatures are very effective in conserving moisture.

Quantity of Light and Plant Structure. All portions of the plant are modified by the amount of light to which they are exposed. The leaves of plants grown in shade or partial shade are thinner and show a thinner cuticle than those of plants grown in full sunlight. The increase in thickness of leaves of sun plants is largely accounted for by the palisade arrangement of the mesophyll. Shade plants are able to carry on their functions by structural modifications favoring increased transpiration while plants exposed to intense light are favored by modifications serving to reduce water losses.

Wiessmann (29) presents interesting data showing the effects of light intensity on the yield performances and structural differences of "light" and "shade" plants in oats. The "shade" plants were grown in a courtyard where they were exposed to direct sunlight for only six hours per day while the "light" plants were grown on the top of a building 11 meters high where they were exposed to the maximum amount of light for the period of vegetation. The differences in the characteristics of these two groups of plants are stated below.

1. Abundance of light favors the production of tillers.
2. Light increases the stability and strength of culms.

3. The length of the culms was favored by the smaller amount of light. The shade plants grew taller.
4. The total yield as well as the weight of all plant structures was greater in the light than in the shade plants.
5. The leaves of the "light" plants produced about 2.5 times as much grain per unit of area as those of the shade plants.
6. The higher yield of grain in the "light" plants is accounted for by the larger number and greater individual weight of kernels produced.
7. Light increases the percentage of roots to total crop.
8. Light decreases the percentage of straw to total crop.
9. The percentage portion of grain and chaff increased with abundant light.

The lodging of plants, especially cereals, is occasioned by a variety of factors as the density of the stand, the rankness of growth induced either by soil conditions, particularly the availability of nitrogen or of climatic conditions or both, the firmness of the soil, as well as by the severity of the climatic factors responsible for the bending over or the falling down of plants. Except where caused by the presence of disease or insect damage, lodging is usually directly induced by wind and rain and frequently by a combination of both. Favorable light relationships are definitely associated with the development of structures and characteristics of stems imparting strength to resist lodging. In addition an excessive growth is very effective in excluding light from the lower portions of plants grown in dense masses.

Effects of Competitive Plant Cover. Plants growing in partial shade of other plants live in an environment quite different from those exposed to full sunlight. They develop in accordance with the modified environmental conditions. Thus the structures of clovers and grasses grown in competition with so-called nurse crops differ materially from those growing in full sunlight. The extent to which light conditions may be modified by a nurse crop is illustrated in Table 16, showing the relative light intensities reaching the upper group of leaves of alfalfa and clover plants grown with and without the indicated nurse crops. The relative vigor of the young leguminous plants at the time of harvest of the respective nurse crops agreed with one exception with the amount of light available to them. The exception was in evidence in the case of the flax nurse crop. It is interesting to note that under the moisture conditions prevailing in northern Idaho, that is, where the vegeta-

tion rhythm is interrupted by a period of summer drought, both the red clover and alfalfa plants established in competition with flax were decidedly less vigorous than those grown with the other nurse crops even though the flax plants allowed more light to reach the legumes. The shallow-rooted flax plants were in more direct competition for soil moisture during the summer drought period than the deeper rooted cereal nurse crops. In this particular instance special moisture conditions constituted the main factor determining the relative development, vitality, of the clover and alfalfa plants. This condition offers another example of a fact pointed out on several occasions, namely, that a crop response may be due not to the action of one factor but to the effects of a variety of factors.

TABLE 16. RELATIVE LIGHT INTENSITIES MEASURED AT THE LEVEL OF THE TOP LEAVES OF RED CLOVER AND ALFALFA PLANTS AND THE RELATIVE VIGOR OF THESE PLANTS AT THE END OF THE FIRST SEASON ESTABLISHED WITHOUT AND WITH THE NURSE CROPS INDICATED. THE MEASUREMENTS WERE TAKEN ON THE UNIVERSITY FARM AT MOSCOW, IDAHO, AT 2:00 P.M. ON JULY 2, 1937.

Nurse Crop	*Stage of Development of Nurse Crop*	*Red Clover*		*Alfalfa*	
		Light Intensity, in Foot-Candles	Vigor of Plants, in Per Cent	Light Intensity, in Foot-Candles	Vigor of Plants, in Per Cent
Without nurse crop		10,800	100	10,800	100
Alaska peas	Pod	5,000	90	7,000	90
Perfection peas	Flower	4,800	85	7,000	90
Trebi barley	Head	3,300	70	2,700	60
Federation wheat	Head	3,000	65	3,000	60
Markton oats	Head	1,800	40	1,500	50
Pacific Bluestem wheat	Jointing	900	30	1,800	40
Flax	Flower	3,600	25	6,000	25
Federation wheat in alternate drill rows	Head	3,600	55	5,100	65
Markton oats in alternate drill rows	Head	2,100	50	1,500	45

In areas of summer precipitation, flax makes a good nurse crop. Under those conditions, that is, when the intense competition for moisture is reduced, the grasses and legumes established with it respond in accordance with the light conditions of their habitats.

The effects of relative abundance of light on the resulting structures of plants have been indicated. Plants growing in partial

shade develop structures common to shade plants. The leaves especially are readily modified, becoming larger and thinner in the shady habitat. The environment of grass and leguminous plants growing in the partial shade of competitive crops changes abruptly with the removal of these crops. Not infrequently the transition thus induced is too great for the tender plants to withstand. If the removal of the nurse crop occurs during periods of less intense sunlight, that is, during an interval of cloudy weather, the sudden change in environment has no detrimental effects. The plants are then able to adjust themselves to their new environment. The reflection of sunlight from the stubble of cereal nurse or competitive crops definitely increases the intensity of the light and also the temperature, thus increasing the stress and need for moisture which is often limited during this critical period in the life of young grass and leguminous plants.

The ability of plants to grow and survive in partial shade is often accounted for by differences in their vegetative rhythms as compared with the rhythms of the taller plants producing the shade. Grasses able to develop early in spring may build up a sufficient carbohydrate reserve in their systems before the leaves of trees above them develop enough to exclude much light. Thus Moreillon (17) presents data showing the loss of dry fodder from grasses growing under spruce trees to amount to 88 per cent as compared to a loss of only 30 to 40 per cent for grasses growing under larch trees. The grasses under the larch trees complete a part of their vegetative rhythm prior to the time that the trees develop their needles. Furthermore the relative abundance of light influences not only the quantity but also the quality, chemical composition, of the forage produced.

Measurement of Light Intensity and Duration. The intensity of light is difficult to evaluate. Both the quantity and quality of the light reaching plants comes into play. Furthermore, it is desirable to have available for habitat studies not only light readings at the moment of the determination but continuous records extending over a period of hours or days. Photoelectric cells and appertaining recording equipment are recommended for the continuous evaluation of the light factor. Such equipment is described by Segelken (22) and by Shelford and Kunz (23). The reader is referred to Weaver and Clements (28) for details relating to the construction

and use of a simple photometer for the momentary measurement of light intensity.

Various investigators have evaluated light intensities on the basis of the difference in the loss of water from standard, white, and blackened spherical atmometer cups. The blackened atmometer cup is covered with lampblack. While this method provides a rough index of intensity over a period of time it does not lend itself to momentary evaluations. Furthermore, the intensity of light is evaluated strictly on the basis of the heat rays striking the atmometer cups and can for that reason be expected to yield reliable data only insofar as the heat rays correlate with the chemically active rays. That this correlation is by no means complete is brought out in Fig. 44.

The duration of sunshine is measured by means of a sunshine duration transmitter. This instrument was devised by C. F. Marvin of the United States Weather Bureau. It consists essentially of a differential air thermometer enclosed within an evacuated glass sheath, with platinum wire electrodes fused into the column at the center. When connected electrically to a sunshine recorder, a continuous record of the duration of sunshine may be obtained.

LENGTH OF DAY

Latitude and Length of Day. Owing to the spheroidal shape of the earth and the inclination of its axis, the duration of the light period, that is, the length of day, varies from 12 hours at the equator to increasing lengths at the higher latitudes to finally continuous sunlight throughout the 24-hour period at the poles during the middle of summer. Thus in the tropics plants are exposed to sunlight half of each day, while Arctic plants grow in nearly continuous light throughout the short summers. This results in actually greater amounts of insolation at the higher latitudes than in the tropics at the summer solstices, June 21 and December 21 for the northern and southern hemispheres, respectively.

In the tropics the length of day remains constant or nearly so for all seasons of the year. At the higher latitudes the length of day increases up to the summer solstice and then decreases. Thus plants growing more or less from the time of the beginning to the end of the growing season develop at first under increasing and after the middle of summer under decreasing lengths of days.

The rapid midsummer growth of plants at high latitudes is no doubt correlated with the long day and associated temperature conditions. Albright, in two papers (1 and 2), describes the unusually rapid growth of various field and garden crops in northern Canada, near the Arctic Circle.

Photoperiodism and Photocritical Periods. Light may influence plant behavior by its intensity, its composition, and by its continuity or duration for any 24-hour period. These variables in the light factor together with the temperature and other environmental conditions determine not only the quantity of photosynthetic material formed but also the utilization of these materials.

The response of plants to the relative length of day and night is referred to as photoperiodism. The term was originally used by Garner and Allard (7) in the first of their series of papers on the topic. The length-of-day factor is of special interest in relation to its formative effects; the action of the duration of light is also interesting and of importance to plant distribution in initiating or suppressing sexual reproduction. Certain plants require relatively long days for successful flowering and fruiting, others are more or less indifferent to light duration, and still others begin to flower only as the length of the summer days decreases. The first group are referred to as long-day and the last as short-day plants, while the so-called ever-bloomers occupy a position intermediate between the two or show some features of both. The long-day plants include those normally coming into the flowering stage in late spring or early summer. Typical examples are the radish, the smaller cereals, red clover, and the common grasses of northern origin. The late-summer-blooming annuals such as tobacco, ragweed, and certain varieties of soybeans continue to develop only vegetatively during the long summer days at higher latitudes; the flowering stage is not initiated until the length of the days decreases in late summer or early autumn. They are typical short-day plants. The particular length of day required under normal conditions to initiate flowering is referred to as the photocritical period.

The term "photocritical period" must be employed with a degree of caution. Garner (6) states that, while

". . . it is true that there is a fairly definite optimum length of day for flowering, . . . generally speaking there is also a wide range in

day length on either side of the optimum in which flowering takes place with more or less facility. . . . In many species representing both the long-day and the short-day types, it has been found that under suitable conditions a variation in day length of not more than one hour (or even less) constitutes the critical range, on the two sides of which definite contrast in response is obtained. On the one side the plant flowers readily while on the other side it tends to remain in the vegetative stage. The important point in this connection is that the group of plants which we have been in the habit of classing as the long-day type flower only when exposed to day lengths in excess of the critical, while the short-day plants are able to flower only under shorter day lengths than the critical. In the present stage of our knowledge of the subject this would seem to furnish a simple and logical basis for differentiating between the two groups of plants."

It is necessary to point out again that the light factor operates in connection with the temperature factor. That this is the case in the regulation and balance between vegetative and reproductive types of activity in plants is evident. The relationship of the temperature and the length-of-day factors to spring and fall flowering is brought out by Garner and Allard (8) in the following paragraph.

"Broadly speaking, in cool temperate regions short-day plants will flower chiefly in the fall rather than in the spring because of the lag in temperature rise in spring as compared with the lengthening of the day. In other words in spring the day length is likely to become too long for flowering of short-day plants before the temperature has risen sufficiently to permit plants to become active. This is true more particularly of the annuals and those herbaceous perennials which require considerable vegetative development as an antecedent to flowering. That plants of these types which regularly flower in the fall will actually flower in the spring when the obstacle of low temperature is removed has been demonstrated in a number of cases."

Length of day or the light period has decided effects on the content of soluble carbohydrates, the form of the carbohydrate present, and on the acidity relations in plants (Nightingale, 18, Garner *et al.*, 9).

Photoperiodism and Plant Distribution. Adaptation has been defined by the degree of correlation existing between the vegetation rhythms of plants involved and the climatic rhythm of a region. Length of day makes up one of the components of the climatic

rhythm and exerts selective influences. Certain plants may fail to fit into given environments on account of their inability to establish the required balance between vegetative and reproductive activities in relation to the prevailing length of day and will for that reason be excluded. Trumble (26) reports from Australia that "at the Waite Institute it has been observed that herbage plants from European and North American sources may fail to flower and set seed normally, although supplied with abundant water. Examples are *Phalaris arundinacea*, *Avena elatior*, *Agropyrum tenerum*, and *Bromus inermis*. This is also true of ecotypes or varieties of *Lolium perenne*, *Dactylis glomerata*, *Phleum pratense* and cereals from northern European sources." On the other hand, Forster *et al.* (5) and Jenkin (13) point out that types from southern Australia, when grown in England and Wales, usually run to stem and seed rapidly, with comparatively little vegetative growth.

The Utilization of Artificial Light. Natural daylight may be advantageously supplemented by means of electrical illumination for purposes of hastening plant development. It has special value in the growing of plants in the greenhouse during the winter months where it may be employed to supplement the generally low intensity of the light during the hours of the day as well as for the purpose of lengthening the days. The installation of electric lighting in many instances results in a more efficient utilization of greenhouse space. Plant breeders have made good use of artificial illumination. With its help several generations of plants may be grown in the time interval usually required for the production of a single generation.

The extent to which artificial illumination may hasten the development of wheat plants is brought out in Table 17, taken from Klages (14). Table 17 also serves to bring out an interesting difference in the light response of spring and winter wheat varieties. The plants in question were exposed to the light given off by 500-watt, nitrogen-filled tungsten lamps fitted with large enameled shades. The lights were on from 5 : 00 P.M. to 8 : 00 A.M. To guard against temperature differences, the lamps were held at a height of four feet above the highest portions of the illuminated plants. The employment of electric light reduced the time interval between the date of planting, November 22, to heading to the extent of 75 per cent for the spring as compared to a reduction of only

29 per cent in the case of the winter wheat varieties. It is interesting to note that varietal differences within the spring and winter types did not significantly influence the percentage reduction in the time interval required for the plants to reach the heading stage.

TABLE 17. EFFECT OF ELECTRICAL ILLUMINATION ON THE REDUCTION OF THE TIME INTERVAL REQUIRED FROM PLANTING TO HEADING OF SPRING AND WINTER WHEAT VARIETIES GROWN IN THE GREENHOUSE IN WINTER (Klages)

Varieties	*Number of Days from Planting to Heading*		*Percentage Reduction in Time because of Artificial Illumination*
	Without Artificial Illumination	With Artificial Illumination	
Spring wheat varieties			
Wisconsin Wonder	144	35	75.69
Preston	181	44	75.69
Marquis	179	48	73.18
Kota	184	46	75.00
Winter wheat varieties			
Minturki	185	131	29.19
Red Wave	187	135	27.81
Turkey Red	192	137	28.65
Hardy Northern	190	133	30.00

REFERENCES

1. Albright, W. D., "Gardens of the Mackenzie," *Geog. Rev.*, 23:1–22 (1933).
2. ———, "Crop growth in high latitudes," *Geog. Rev.*, 23:608–620 (1933).
3. Blackman, F. F., and G. L. C. Matthaei, "On vegetative assimilation and respiration," *Proc. Roy. Soc. London*, B 76:402–460 (1905).
4. Boysen-Jensen, P., "Studies on the production of matter in light and shade plants," *Bot. Tidskr.*, 36:219 (1918).
5. Forster, H. C., M. A. H. Tincker, A. J. Vasey, and S. M. Wadham, "Experiments in England, Wales and Australia on the effect of length of day on various cultivated varieties of wheat," *Ann. Appl. Biol.*, 19:378–412 (1932).
6. Garner, W. W., "Comparative response of long-day and short-day plants to relative length of day and night," *Plant Physiol.*, 8:347–356 (1933).

7. Garner, W. W., and H. A. Allard, "Effect of the relative length of day and night and other factors of the environment on growth and reproduction in plants," *Jour. Agr. Res.*, 18:553–606 (1920).
8. ———, "Further studies in photoperiodism, the response of the plant to relative length of day and night," *Jour. Agr. Res.*, 23:871–920 (1923).
9. ———, C. W. Bacon, and H. A. Allard, "Photoperiodism in relation to hydrogen-ion concentration of the cell sap and the carbohydrate content of the plant," *Jour. Agr. Res.*, 27:119–156 (1924).
10. Hann, J., *Handbook of Climatology*, Part 1, "General Climatology," trans. 2d rev. German ed. by Robert DeCourey Ward. Macmillan, New York, 1903.
11. Harder, R., "Kritische Versuche zu Blackmans Theorie der "begrenzenden Factoren" bei der Kohlensäureassimilation," *Jahrb. wiss. Bot.*, 60:531–571 (1921).
12. Henry, A. J., J. B. Kincer, H. C. Frankenfield, W. R. Gregg, B. B. Smith, and E. N. Munns, "Weather and climate," *U. S. Dept. Agr. Yearbook*, 1924:457–558.
13. Jenkin, T. J., "Perennial rye-grass at Aberystwyth," *Welsh. Jour. Agr.*, 6:140–165 (1930).
14. Klages, K. H. W., "Metrical attributes and the physiology of hardy varieties of winter wheat," *Jour. Amer. Soc. Agron.*, 18:529–566 (1926).
15. Lundegårdh, H., *Klima und Boden in ihrer Wirkung auf das Pflanzenleben.* Gustav Fischer, Jena, 1925.
16. MacDougal, D. T., *Practical Text-Book of Plant Physiology.* Longmans, New York, 1901.
17. Moreillon, M., "Influence de l'ombrage sur la valeur des gazons dans les pâsturages boises," *Jour. Forest. Suisse*, 70:131–142 (1919).
18. Nightingale, G. T., "Light in relation to the growth and chemical composition of some horticultural plants," *Proc. Amer. Soc. Hort. Sci.*, 1922:18–29.
19. Pulling, H. E., "Sunlight and its measurement," *Plant World*, 22:151–171 and 187–209 (1919).
20. Raunkiaer, C., *The Life Forms of Plants and Statistical Plant Geography.* Clarendon Press, Oxford, 1934.
21. Schimper, A. F. W., *Plant Geography upon a Physiological Basis*, trans. German by W. R. Fisher. Clarendon Press, Oxford, 1903.
22. Segelken, J. G., "The determination of light intensity," *Ecology*, 10:294–297 (1929).
23. Shelford, V. E., and J. Kunz, "Use of photoelectric cells for light measurement in ecological work," *Ecology*, 10:298–311 (1929).

24. Shirley, H. L., "The influence of light intensity and light quality upon the growth of plants," *Amer. Jour. Bot.*, 16:354–390 (1929).
25. Tippett, L. H. C., "On the effect of sunshine on wheat yield at Rothamsted," *Jour. Agr. Sci.*, 16:159–165 (1926).
26. Trumble, H. C., "The climatic control of agriculture in South Australia," *Trans. Roy. Soc. So. Australia*, 61:41–62 (1937).
27. Warming, E., *Oecology of Plants.* Clarendon Press, Oxford, 1909.
28. Weaver, J. E., and F. C. Clements, *Plant Ecology.* McGraw-Hill, New York, 1929.
29. Wiessmann, H., "Einfluss des Lichtes auf Wachstum und Nährstoffaufnahme beim Hafer," *Landw. Jahrb.*, 53:183–190 (1919).

Chapter XIX

AIR MOVEMENT

Introduction. Wind and air movement in general constitutes an ecological factor of both local and regional significance. The main climatic types over large regions are determined by the movements of large masses of air. Such movements are called forth mainly by differences in temperature. Temperature variations result in differences in the density of the air exerting a pressure phenomenon conveniently evaluated by means of a barometer. A line drawn through points having the same value of atmospheric pressure is known as an isobar. The isobars always encircle areas of low and of high pressure.

Air flows from regions of high to regions of low pressure. Since the variations in pressure or weight of the atmosphere are evaluated by means of barometric pressures, the difference in air pressure which causes air movements, or winds, is called the barometric gradient. The movement of air may be compared to the movement of flowing water, that is, down a gradient.

The movements of air caused by heating, cooling, expansion, and contraction, as well as the massing of the air in one locality and the counterbalancing depressions formed in another, include the general or planetary movements. Obviously, the general movements of air as well as the composition of these air masses especially with regard to their moisture content and their temperature are of great geographical importance. The choice of crops and production of crops in any given area may also be greatly influenced by the prevailing wind conditions. The wind velocity especially at critical periods and insofar as it may influence loss of moisture from the plant or soil is of great practical importance. Certain special types of wind such as the chinook, foehn, monsoon, or hot winds, as the sirocco, have decided effects on local crop production. In addition to this, catastrophic air movements

such as tornadoes or hurricanes are of significance to crop production in limited areas.

Wind erosion is occasioned by the character of the soil, by the type of cover, and by the velocity of the wind. The possibilities and actual devastating effects of wind erosion have a very direct bearing on the agricultural utilization of given areas. The choice

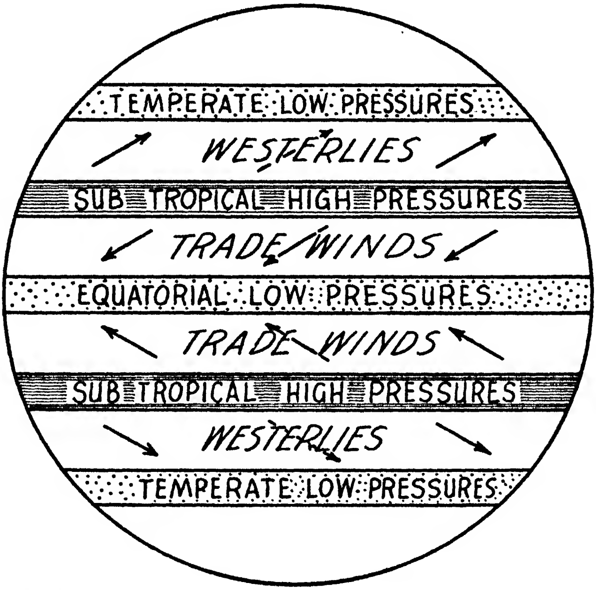


Fig. 45. Diagrammatic arrangement of wind systems or pressure belts of the generalized globe. (Reproduced from Kendrew, *Climate*, by permission of the Oxford University Press.)

of crops, whether grass cover, cereals, or cultivated crops, as well as the methods of handling these crops are directly influenced by danger of wind erosion.

General Air Movements and Their Relations to Climate. The winds of the earth blow in directions determined by differences in pressure. The pressure distribution is, as has been indicated, closely linked with temperature phenomena. And to these great forces must be added the influence of the rotation of the earth. It should be kept in mind that the magnitude of the rotational force increases rapidly with the latitude; as a result of this, the rotation of the earth has a greater effect in deflecting the great wind systems as the higher latitudes are approached. The general

circulation of the atmosphere is largely determined by the set of forces indicated above. General more or less well-defined broad belts are recognized encircling the globe. These belts of general circulation or wind systems are shown diagrammatically in Figs. 45 and 46, taken from Kendrew (4). Figure 45 outlines the general belts, while Fig. 46 presents a plausible explanation of the movement of the air masses on a generalized or imaginary globe, that is, if the surface were homogeneous. "It must be admitted that the general circulation of the atmosphere," states Kendrew, "is by no means fully understood, and other presentations of some of its features than the scheme of Fig. 46 have been given by meteorologists."

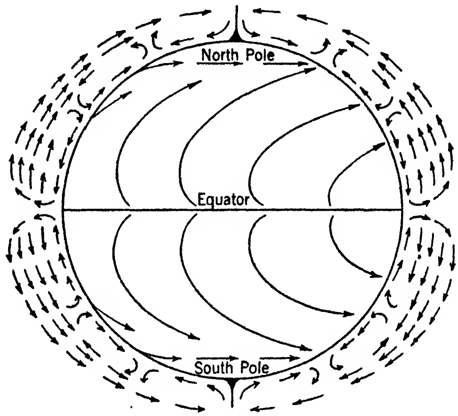


FIG. 46. Idealized diagram of the general circulation of the atmosphere over the homogeneous globe. (Reproduced from Kendrew, *Climate*, by permission of the Oxford University Press.)

The explanation offered by Kendrew for the more or less definite development of the wind systems of the globe is given in the following two paragraphs.

> "The air that is warmed and expanded over the Equator rises, and flows away in the higher strata of the atmosphere towards higher latitudes, where the cold causes contraction, descent and an inflow aloft (Fig. 46). Thus there is set up a general movement from the Equator towards the Poles in the higher atmosphere, and it is probable that the air pressure at heights above 12,500 feet decreases steadily from Equator to Poles. But all moving bodies come under the influence of the rotation of the earth, the magnitude of the rotational force increasing rapidly with the latitude. Hence in their poleward journey these air currents become deflected more and more towards the east, until in high latitudes a gigantic circumpolar whirl is set up. Another influence now makes itself felt, for centrifugal force is developed in a rotating mass of this kind, and the air, instead of reaching its Polar goal, tends to be thrown back towards the Equator, since its speed is much greater than that of the earth below. The upper winds are therefore moving eastward and poleward in low latitudes, eastward with a slight equatorward component in high latitudes. The result is

a piling up of air between the thermal outflow over the Equator and the dynamical, centrifugal, movement in high latitudes, giving high atmospheric pressure in the sub-tropics.

"Poleward of these high-pressure belts pressure becomes less towards the poles, the centers of the circumpolar whirl, and produce an increase of pressure, slight but quite sufficient to effect a change in the wind direction from westerly to easterly."

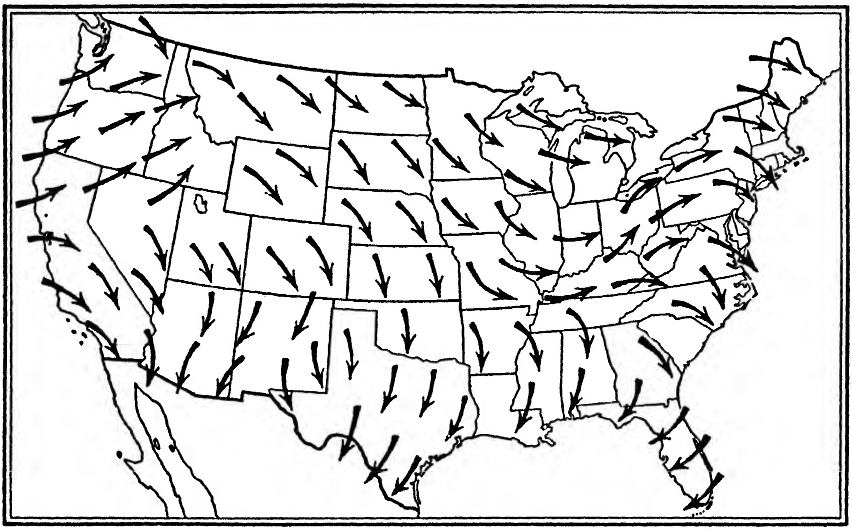


FIG. 47. Prevailing winds over the United States in January. (Reproduced from Ward, *The Climates of the United States*, by permission of Ginn and Company.)

Because of temperature changes, the pressure belts swing some 5 to 10° toward the north during the summer months in the northern and to the south during the summer months in the southern hemisphere.

It is possible here to give only a broad outline of the wind systems of the globe; the reader is referred to standard texts on meteorology for a more detailed treatment of this topic. A general knowledge of wind systems is of importance to the understanding of climatic types. The movements and compositions of great masses of air in relation to bodies of water and land areas are of prime importance in determining the main characteristics of the climate of any given locus. Such movements of air masses are greatly influenced not only by the general wind systems of the globe but also by the topographical features of the land areas in that mountain ranges

and other barriers may deflect the movement of air masses from their general course.

The movement of great masses of air over the large continents is quite variable and greatly influenced by the seasons and by topographical features. This is well illustrated in Figs. 47 and 48 taken from Ward (9), giving the prevailing winds over the area of the United States in January and July.

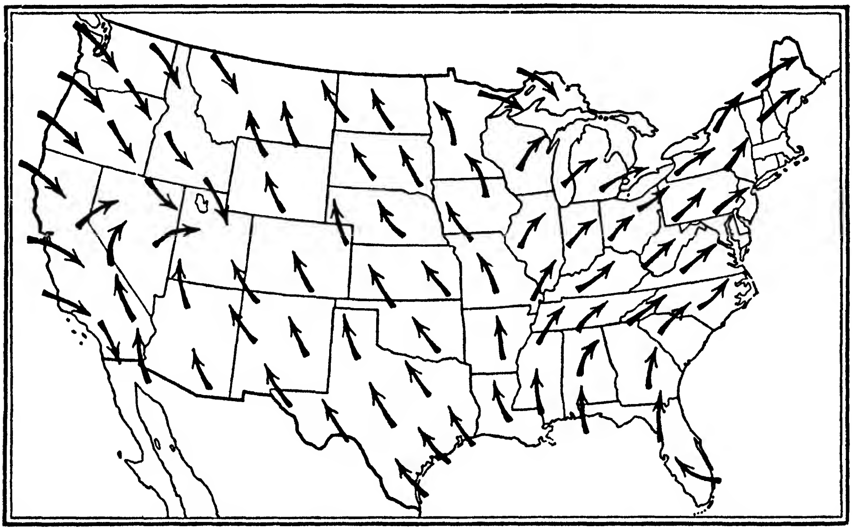


FIG. 48. Prevailing winds over the United States in July. (Reproduced from Ward, *The Climates of the United States*, by permission of Ginn and Company.)

Migratory Cyclones and Anticyclones. The pressure phenomena and wind belts discussed in the preceding paragraphs represent the normal, or undisturbed, state of affairs. In many parts of the world, this normal condition is frequently disturbed by migrating great masses of air, or atmospheric whirls, known as cyclones and anticyclones. The centers of these disturbances are in constant motion.

Piston (7) gives a clear-cut definition of these two terms. "The cyclone consists of a mass of air several hundred miles in diameter whirling about a center where the pressure is low, and the anticyclone is a mass of somewhat greater diameter whirling about a center where the pressure is high. The cyclone is usually associated with wet or cloudy weather and the anticyclone with dry clear weather." In cyclonic areas the air moves toward a region of low

pressure, with the winds blowing in all directions toward the center; in anticyclonic areas the reverse is the case — the air moves outward from a region of high pressure, with the winds blowing in all directions from the center. The rate of air movement is determined by the barometric gradient. These two types of disturbances migrate over long distances over more or less well-defined routes. The paths of the cyclonic storms in the middle latitudes, that is, in the areas of the prevailing westerly winds, extend from the west to east. In the north temperate zone, the cyclonic storms encircle the earth in a belt which dips toward the south over the continents and turns north over the oceans. Their paths become somewhat diffused over great bodies of land as in Eurasia. As the areas covered by the anticyclonic movements are greater than those covered by the cyclones, the northern portion of the United States is under the influence of anticyclones about 60 per cent of the time, and of cyclones about 40 per cent.

The cyclonic movements and cyclones here discussed should not be confused with the violent storms sometimes referred to by that name. These violent storms usually covering but limited areas are properly called tornadoes.

The tropical cyclones are quite different from the cyclonic movements of temperate latitudes. Wind velocities of the temperate-zone cyclones rarely rise to 30 miles per hour; the pressure at the center of the cyclone is usually less than an inch below normal. In other words, the winds of extratropical cyclones are mild. Tropical cyclones, while of infrequent occurrence, usually have violent winds. The pressure at the center may be two inches or more below normal. In tropical cyclones, the wind is of destructive force, and sometimes attains a speed of 200 miles per hour. As much as ten or more inches of rain may fall in 24 hours. These are the hurricanes of the tropics, referred to as typhoons in Asiatic waters.

Areas in the direct path of cyclonic movements such as the northeastern section of the United States and the countries of northwestern Europe have variable weather, that is, the weather changes at frequent intervals. Areas out of the main paths of these movements have weather that is more uniform, even to the extent of being monotonous in nature. The cyclonic movements are

of great importance in determining not only the kind but also the degree of variability of the weather.

Since the terms "weather" and "climate" were used in the above discussion, it is necessary to distinguish between them; they are not interchangeable. The term "weather" refers to the condition of the atmosphere with respect to its temperature, moisture content, pressure, light conditions, its movement, etc., at any given moment. The term "climate," on the other hand, connotes the average of the weather conditions as experienced in a definite geographical location and with the passing of the seasons. The characteristics of a climate are designated by the means of the factors determining the weather. After these have once been established by means of records extending over a period of ten or more years they remain fairly constant; or, as it is stated by Köppen (5), the weather changes, while the climate remains.

Measurement of Wind Velocity. The three-cup-type Robinson anemometer is almost universally used for the measurement of wind velocity. The speed of rotation of the cups of this instrument is nearly directly proportional to the velocity of the wind. The central shaft supporting the cups is connected by a train of gears to a revolving dial on which the total wind movement is shown. It is used, together with the time between observations, for calculating average velocity. The instrument may be fitted with a cam on the dial so arranged as to close an electric circuit once for every mile of wind movement. With the aid of an electromagnet, a recording pen will inscribe a notch for every mile of wind movement on a record sheet of a revolving time drum. The anemometer may also be provided with an appliance to operate a buzzer at intervals of one-sixtieth mile. This device is of special help in the evaluation of high wind velocities.

The deflection anemometer is useful for giving a quick but rather rough measure of wind velocity; it has the advantage of being portable.

A continuous record of the direction of the wind can be obtained by the use of the recording wind vane used by the United States Weather Bureau.

The Beaufort Wind Scale. The Beaufort scale was originally devised by Admiral Beaufort in 1805 to advise sailing masters of the kind and spread of sail that ships of the line might carry and

their probable speed under such sail. It was recently revised for the benefit of weather observers and is no doubt of some value in that it provides a guide to probable wind velocities in the absence of anemometers. The scale ranges from 0, for calm, to 12, to designate a hurricane. It is graduated in accordance with such physical effects of the wind as the movement of smoke, leaves, branches and trunks of trees, and in the case of high velocities the extent of damage to structures. Thus a moderate breeze, Beaufort scale number 4, with a wind velocity of 18 to 23 miles per hour, raises dust and moves small branches of trees. A moderate gale, scale number 8, wind velocity 40 to 48 miles, breaks twigs from trees, etc.

Effects of Wind on Plant Distribution. "Wind," states Warming (10), "exerts an influence upon both the configuration and the distribution of plants." Since the velocity and force of the wind increases with height above the ground level, tall growing plants and especially trees are exposed to both the direct mechanical and the indirect physiological effects of wind to a greater extent than low growing plants. In severe cases the exposure to wind may constitute one of the most important factors determining height of plants and the distribution of vegetation.

The absence of trees in many locations is due to the effects of wind. Since air movements tend to increase the rate of water loss from plants, even of plants in a dormant condition, wind during the winter months when the soil is frozen is especially responsible for the delineation of the boundaries of woodlands in the higher latitudes and in determining the upper limits of tree growth on mountain ranges. Middendorff (6) was the first investigator to recognize the significance of wind in assigning the limits to the extension of forests. Schimper (8) also recognized the importance of wind and especially wind during the winter months to the establishment of limits to tree growth.

That air movements and wind play an important part in physiological drought is evident. In the minimal areas, protection against wind, by topographical features, by living plants such as shelter belts, and even by the remains of portions of plants as crop residues, is of considerable importance to crop growth and survival. Such protection may serve to reduce the velocity of the wind and one of the hazards encountered in crop production in such areas.

The action of wind is not necessarily always detrimental. Wind is effective in the distribution of seeds and of pollen and thus influences the rate of invasion of newly introduced plants.

Wind also constitutes a factor in the dispersing of disease-producing organisms. As a matter of fact, it may carry spores, such as the causal organism of cereal stem rust, over great distances. Prevailing winds from an early to a later crop producing area, especially when uninterrupted by natural barriers as is the case in the Great Plains, provide a most efficient vehicle for carrying the spores of black stem rust of wheat from the lower to the upper portions of this important wheat producing region. In seasons favorable to the development of rust epidemics the disease becomes critical in areas extending from south to north at a rate more or less corresponding with the progressive development of the host plants from the early to the later areas of production.

Physiological Effects of Wind. Wind has both mechanical and physiological effects on plants. The outstanding mechanical effects as related to crop plants are the partial or complete covering of plants by soil particles; the breaking over of plants; the breaking off of portions of plants, as the snapping off of heads in mature cereals; the shattering of seed from mature heads of cereals; the laceration of leaves; the damage to seedling plants by soil particles striking tender portions; and in severe instances the entire removal of young plants from the soil. The most far-reaching physiological effects of wind are correlated with the intensification of vital functions of the plant, especially of transpiration and water loss in general.

Finnell (3) presents data to the effect that high winds may exert greater damaging effects upon plant growth "than would be expected by reason of increased transpiration alone."

In considering the physiological effects of wind on plant growth it is also necessary to consider the loss of water directly from the soil. Soil moisture losses even without a plant cover increase materially with increasing wind velocities.

Wind Erosion. When a dry, partially deflocculated soil unprotected by vegetative cover is exposed to strong or even moderately strong winds, soil particles will be moved. In the last few years, the problem of soil blowing has been brought before the public, especially from the Great Plains area. The problem is,

however, by no means limited to subhumid regions. Even in humid areas sandy soils have long been regarded as actual or potential blow soils.

Plant cover offers the most efficient and permanent protection against soil blowing. If such soils are to be used for the production of cultivated crops, it becomes essential that their organic matter contents be built up so that they will be flocculated and not readily broken up into unit particles. Cultural methods leaving the soil rough and the leaving of crop residues at the surface aid in holding particles in place.

The texture of the soils severely eroded by wind may be changed to a point impairing their usefulness for crop production purposes. Thus Daniel (2), in working with the physical changes in the soils of the southern High Plains, reports that "the drifts from nine different soils that have been shifted at least four times contained 73.0% less silt and clay and 31.28% more sand than the respective virgin surface."

While wind erosion is influenced by the wind factor, it is to be borne in mind that it constitutes also a cropping problem. It is definitely associated with problems of proper land utilization from the standpoints of use for permanent grass cover, cereal production, or use for intertilled crops. As a matter of fact the periodic urgency of the wind erosion question is linked with improper land use in the past; it will continue to present itself as a problem unless either shifts in land use in some cases, or precautionary measures in other instances are taken to prevent its destructive effects. Certain areas in the United States as well as in other countries of the world have been inadvisably used for crop production purposes and thus deprived of their protective native covers. On the other hand, caution should be exercised before large areas are condemned as totally unsuited for crop production. With proper methods many of the areas in which wind erosion may be expected to become a problem periodically can be utilized. Thus Call (1), in speaking of conditions prevailing in the central Great Plains, states that

> "there is no reason to expect that wind erosion will not be controlled in this region unless climatic conditions occur that are much less favorable for the growth of vegetation than those that have prevailed during the past 50 years. The best information available would lead to the

conclusion that while periods of serious wind erosion will occur in the future during times of drought, such periods will not lead to the destruction of the soil or become a major factor that will preclude the utilization of this area for successful crop production."

REFERENCES

1. Call, L. E., "Cultural methods of controlling wind erosion," *Jour. Amer. Soc. Agron.*, 28:193–201 (1936).
2. Daniel, H. A., "The physical changes in soils of the southern High Plains due to cropping and wind erosion and the relation between the $\frac{\text{Sand} + \text{Silt}}{\text{Clay}}$ ratios in these soils," *Jour. Amer. Soc. Agron.*, 28:570–580 (1936).
3. Finnell, H. H., "Effect of wind on plant growth," *Jour. Amer. Soc. Agron.*, 20:1206–1210 (1928).
4. Kendrew, W. G., *Climate*. Clarendon Press, Oxford, 1930.
5. Köppen, W., *Die Klimate der Erde*. Walter DeGruyter & Co., Berlin, 1923.
6. Middendorff, A. T. von, *Reise in dem äussersten Norden und Osten Sibiriens*. St. Petersburg, 1867.
7. Piston, D. S., *Meteorology*. Blakiston, Philadelphia, 1931.
8. Schimper, A. F. W., *Plant Geography upon a Physiological Basis*, trans. German by W. R. Fisher. Clarendon Press, Oxford, 1903.
9. Ward, R. D., *The Climates of the United States*. Ginn, Boston, 1925.
10. Warming, E., *Oecology of Plants*, trans. German by P. Groom and I. B. Balfour. Clarendon Press, Oxford, 1909.

Chapter XX

CLASSIFICATION OF CLIMATE

INTRODUCTION

Objectives in Classification. Being made up of a variety of elements active both as to intensity and time, climate is difficult to classify. The crop ecologist is interested in the factors making up the climatic rhythm from the standpoint of their separate and combined effects on plant growth, especially on the vegetation rhythm of crop plants.

Classification serves to identify and to show relationships. A concise statement of the main characteristics of the climates of adjacent or of widely separated areas showing at a glance their similarities or differences is of great value in the study of ecological crop geography. Such a statement not only provides the student with the most probable reason for the production of a particular crop in a certain area but also reflects on the climatic requirements and the range of adaptation of the crop in question.

Basis for Classification. The outstanding features of the climate of any given region are determined by a number of factors, such as its latitude, its altitude, its proximity to and direction from large bodies of water, and its local topography. The direction of the prevailing winds in relation to land areas is of importance in all instances but affects the climates especially of locations near large bodies of water and in areas where the position and direction of mountain ranges deflect the movement and the temperature of large masses of air.

While the factors indicated above actually determine the main climatic features of a region, they do not provide the best criteria to serve as a basis of any but very general and descriptive classifications. They serve to provide the basis for differentiating, for instance, between marine and continental or woodland and grassland climates, but do not give detailed and definite enough criteria for

the numerical evaluation of climatic features upon which a more comprehensive classification may be based. Comprehensive classifications of climates such as Köppen's (10) and Thornthwaite's (17 and 18) require the actual evaluation of the intensities of the two most important factors determining the weather from day to day and with the passing of the seasons, namely temperature and precipitation. These two factors are of course of prime importance in determining the distribution of plants. A classification based on factors that can be evaluated with precision and treated mathematically has the advantage of lending itself to symbolism. The employment of symbols for the designation of climatic types has the obvious advantage of simplicity in that a system of codification may be employed to designate the main features of the climates classified. While it is recognized that climatic factors other than moisture and temperature conditions come into play in the evaluation of climate and have their specific effects on the weather at any given time and on plant responses, it is also evident that all climatic factors are more or less interrelated and to a high degree correlated and conditioned as to their respective intensities with moisture and temperature conditions.

Limitations of Climatic Classifications. To be of greatest value, designated classes of climates must be definite, yet not too complex. The number of classes should be held to a minimum. A classification based on too many factors and on too many fine distinctions negates the very objectives of classification. Classifications are in no way expected to take the place of descriptive treatises on the climates; they have application primarily in broad systematic groupings showing relationships between the various regions with respect to climatic similarities and differences. Thus no classification of climate will take the place of such extensive works dealing with the climates of the continents as presented by Hann (3) and Kendrew (9).

In a designation of groups of climates it must be recognized that the lines of demarcation of necessity are based on the average values or intensities of the climatic features considered. This should not lead to the conclusion that variability of the climatic features is not considered important. Variability both within and between seasons is of great significance to the agricultural utilization of any given area. The inclusion of a measure of variability

into a system of classification, however, would make such a system too complex for general application. Whenever climatic types are cartographically delineated it should be understood that the boundary lines between the types are not sharp; but rather, that they represent transition zones and appear in their true rôle as indicators of direction of change.

CLASSIFICATION BASED ON THE RELATIVE DISTRIBUTION OF LAND AND WATER

Marine Climates. "The influence of latitude," states Ward (22), "may be wholly overcome by the effects of land and water. Land and water are fundamentally different in their behavior regarding absorption and radiation." This is accounted for by the difference in the specific heat and the greater heat-holding capacity of water as compared to land and soil.

The equalizing effect of bodies of water on temperature is further enhanced by the fact that water is able to store for future release a greater quantity of heat than soil. Temperature changes penetrate the soil only a few feet, while they reach great depths in water. This is due to ascending and descending currents in water. In soil the heat from the surface layers can reach the lower strata only by conduction.

Ward (22) points out that the climates of large continental areas of the middle and higher latitudes are characterized by great seasonal fluctuations in temperature. "They are distinctly radical in their tendencies. The land areas absorb much heat, but part with it readily. The oceans, on the other hand, cool but little during the night and in winter. They take in but little heat, and part with it reluctantly. Conservatism in temperature is a distinctive feature of marine climates."

The outstanding characteristic of marine climates is the uniformity or smaller range of both the diurnal and seasonal temperatures. Continental climates show wide ranges. The other significant difference between these two climates, also traceable to the fundamental differences in the behavior of land and water regarding absorption and radiation of heat, is found in the variation in the shape of their annual temperature curves. Temperatures of continental climates attain their maxima about one month after the date of the sun's maximum altitude; they attain their minima

in a little less than a month after the sun's lowest altitude. In marine climates the delay in the time of maxima and minima is much greater. The high temperatures of the year do not occur until August as contrasted to July for the continental climates. The lowest temperatures in marine climates do not occur until two, or even three, months after the greatest declination of the sun, that is, in February or March.

Not all land areas in close proximity to large bodies of water have marine climates. The climates of such areas, that is, whether marine or continental, are determined primarily by their direction from the water in relation to the prevailing wind. Likewise, the presence of mountains in the way of onshore winds has decided effects. The onshore winds can exert their equalizing effects inland only if their paths are not obstructed by mountain ranges. The narrow north Pacific coastal slope of this continent, even as far north as the lower portion of Alaska, has a marine climate. On the lee side of the Cascade range the climate is decidedly continental. The effect of a break in a mountain range, on the other hand, is well illustrated by the effects of the Columbia River gorge. The relative mildness and transitional character of the climates of the Columbia River basin and the Palouse region can be accounted for by the fact that the onshore winds can penetrate inland through the gap cut by the Columbia through the Cascade range.

The effect of onshore and offshore winds is well illustrated by the difference in the climates of the Pacific coastal slope as contrasted with those of the Atlantic coastal belt; in the first case the climates are marine, in the latter case, continental. As stated by Ward (22), "The influence of the Atlantic Ocean is much diminished by the fact that the prevailing winds are offshore. Hence, it follows that there is not very much of the tempering effect usually associated with the conservative ocean waters. The Atlantic coastal belt, except when the winds temporarily blow onshore, does not differ very much from the interior." The effects of onshore winds are also influenced by the temperature of large bodies of water as modified by latitudes and ocean currents.

The effect of onshore winds on winter temperatures is evident from a glance at Fig. 49, showing the mean temperatures in degrees Fahrenheit for the month of January in different parts of the world.

The isotherms of the northern hemisphere turn sharply to the south along the Pacific coast of North America and in northwestern Europe. On the lee side of the continents, that is, along the Atlantic coast in North America and the northern coast of western Asia, they turn to the north. The isotherms also show that the marine climates extend farther inland in northwestern Europe than along the mountain-braced Pacific coast of North America. Owing to the absence of mountain barriers, the marine climates of the lowlands along the Atlantic Ocean and the North Sea merge gradually into the transitional or littoral, and as the plains of Russia are approached into the true continental type. In North America, the lines of demarcation between these two types of climates are sharp.

Figure 49 also shows that the temperatures over land areas in summer are higher than over the adjacent oceans. Note the trend of the isotherms in the southern hemisphere.

Continental Climates. These climates take their name from the interior of the continents. Their effects may, however, extend, as has been indicated, right up to the coast line on the lee side of large areas of land.

Since land areas warm up and also cool down more rapidly than water, continental climates are characterized by great ranges of temperature between the winter and summer seasons. Thus according to Visher (20), "western Oregon has a normal seasonal range of only about 18°F (10°C), while South Dakota has a range of 60°F (33°C). The extreme ranges in these places are about 85°F (46°C) and 165°F (91°C) respectively."

The diurnal range of temperatures is also greater in continental than in littoral and marine climates. The effect of the proximity and direction of large bodies of water has been pointed out. Other factors entering to make for greater ranges in daily temperatures are the humidity of the atmosphere and the presence of vegetation. As a general rule the diurnal range in temperature increases with lower humidities and with aridity. Areas with sparse vegetation show a greater range of temperature than those heavily covered.

No general statement can be made relative to the differences in precipitation in marine and continental climates. As indicated by Hann (4) "the amount and frequency of precipitation as a rule decreases inland, but this decrease is so irregular, and depends so

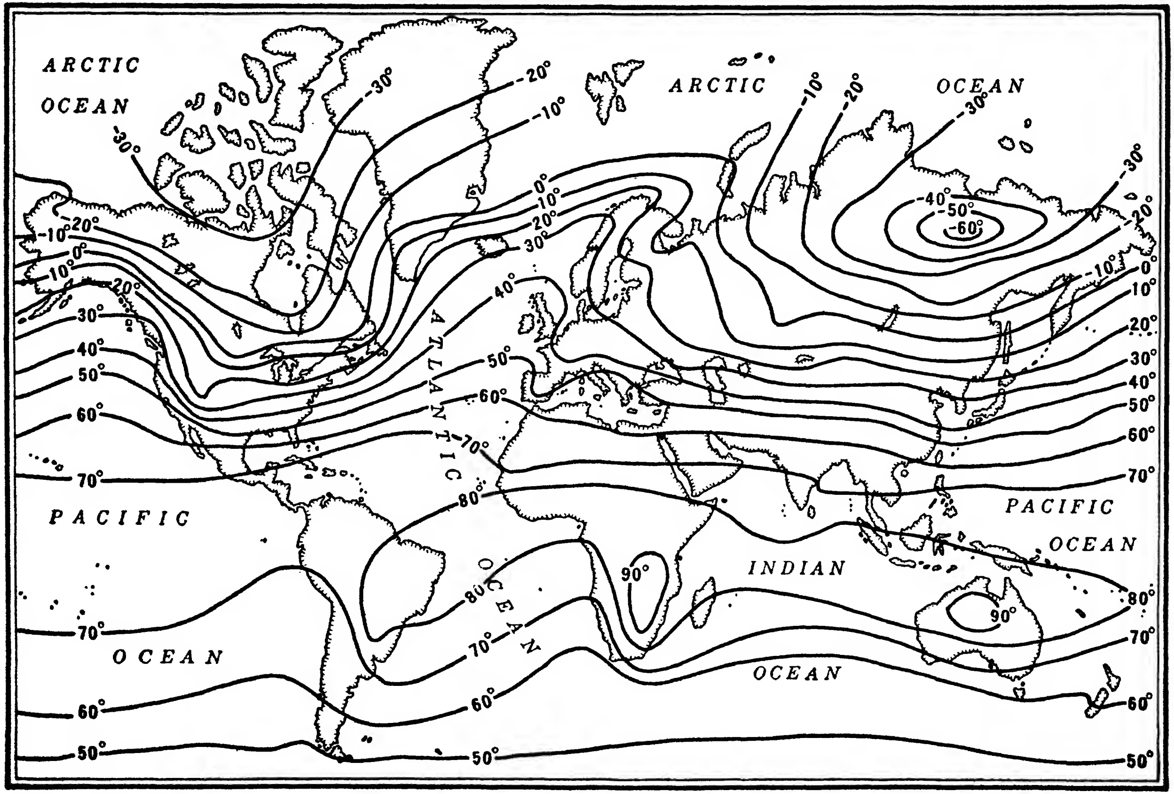


FIG. 49. Isotherms for the mean temperature in degrees Fahrenheit, for the month of January.

much upon the topography; upon the position of mountain ranges with respect to rain-bearing winds, etc., that no general illustrations of this rule can be given."

Mountain Climates. Mountain climates may be regarded as extreme types of continental climates. The prime factor influencing their characteristics is elevation. The seasons are distinct; they are initiated and also end abruptly. Variations in slope are of great importance to the agricultural utilization of areas in mountain regions in that they affect both soil and local climate.

CLASSIFICATION BASED ON NATURAL VEGETATION

Plant Physiognomy and Climatic Conditions. While it is not necessary to become involved here in the controversy relative to the classification of plants into physiognomic forms, it must be recognized, as has been pointed out on other occasions, that life forms are greatly influenced by environmental conditions. The physiognomy, or outward appearance, of the plant cover of any given habitat is determined not only by the visible structure or external morphology of individual species but also by the diversity of the species represented. In a detailed study of environmental conditions it becomes necessary, as pointed out by Clements (1), to consider both the diversity of the species represented and also the altered individuals, the ecads, of the same species. Both indicate differences in conditions and trends.

The index value of natural vegetation for proper land use is well stated by Shantz and Zon (15) in the following paragraph.

> "The natural vegetation of a country, when properly analyzed and classified, may serve a very concrete and practical purpose. As a new country becomes settled the natural vegetation must be replaced gradually by agricultural crops, orchards, pastures, and man-made forests. The suitability of the virgin land for various crops is usually indicated very clearly by the natural vegetation. After a correlation is established between different forms of natural vegetation and various agricultural and forest crops, it provides a means of dividing the country into natural regions of plant growth, which can be used as indicators of the potential capabilities of the virgin land for agriculture and forest production."

Numerous other statements based on detailed experimental data showing the indicator significance of natural vegetation could be given. This is not necessary. It is essential, however, to point out,

in adhering to the general topic of classification of climates, that the natural vegetation of any given locus is not determined by the climate alone. The soil factors also enter into play. Furthermore, the soil conditions both past and present must be considered in the development and maintenance of a native vegetation. These statements are of special significance here. They indicate clearly that any broad classification of climates must be based on regional, rather than local, flora. This definitely limits the number of classes based on natural vegetation, and rightly so. Natural vegetations offer a usable criterion of local climatic and soil conditions rather than a basis for detailed classifications of climates. Nevertheless, when quite distinct, larger types of natural vegetation such as woodlands, grasslands, and deserts are selected, valuable deductions of the outstanding features of the climates of the areas where they constitute the climax can be drawn. Also, the utilization of their habitats for agricultural purposes is definitely associated with their distribution and relative development. Since these groups of vegetation extend over large areas any classification of climates based on them is decidedly regional in nature. The climatic types thus established are of course separated by transition zones, and subtypes may be recognized in places where the native vegetation has been sufficiently analyzed. Thus in the United States climatic conditions in the climax tall-grass prairie, in the mixed prairie, and in the short-grass plains differ materially.

Figure 50, taken from Henry *et al.* (6), gives "a very generalized map of the natural vegetation of the world showing its broader relations to climate." More detailed world vegetation maps are available. An especially clear map is given by Hayek (5) showing the distribution of 16 distinct types of vegetation. The types presented are: cold desert, mats or meadow lands, tundra, dry deserts, steppes, savanna, thorny chaparral half deserts, coniferous forests, summer-green deciduous forests, hard-leaved forests, heather, temperate rain forests, savanna forests, monsoon forests, subtropical rain forests, and the tropical rain forests.

Woodland Climates. A glance at Fig. 50 shows that woodland or forest formations are found in relatively well-watered areas. This is not surprising. Trees expose a large transpiring surface to the atmosphere; great quantities of water are a prime necessity. This is true especially for deciduous trees. Certain of the conifers

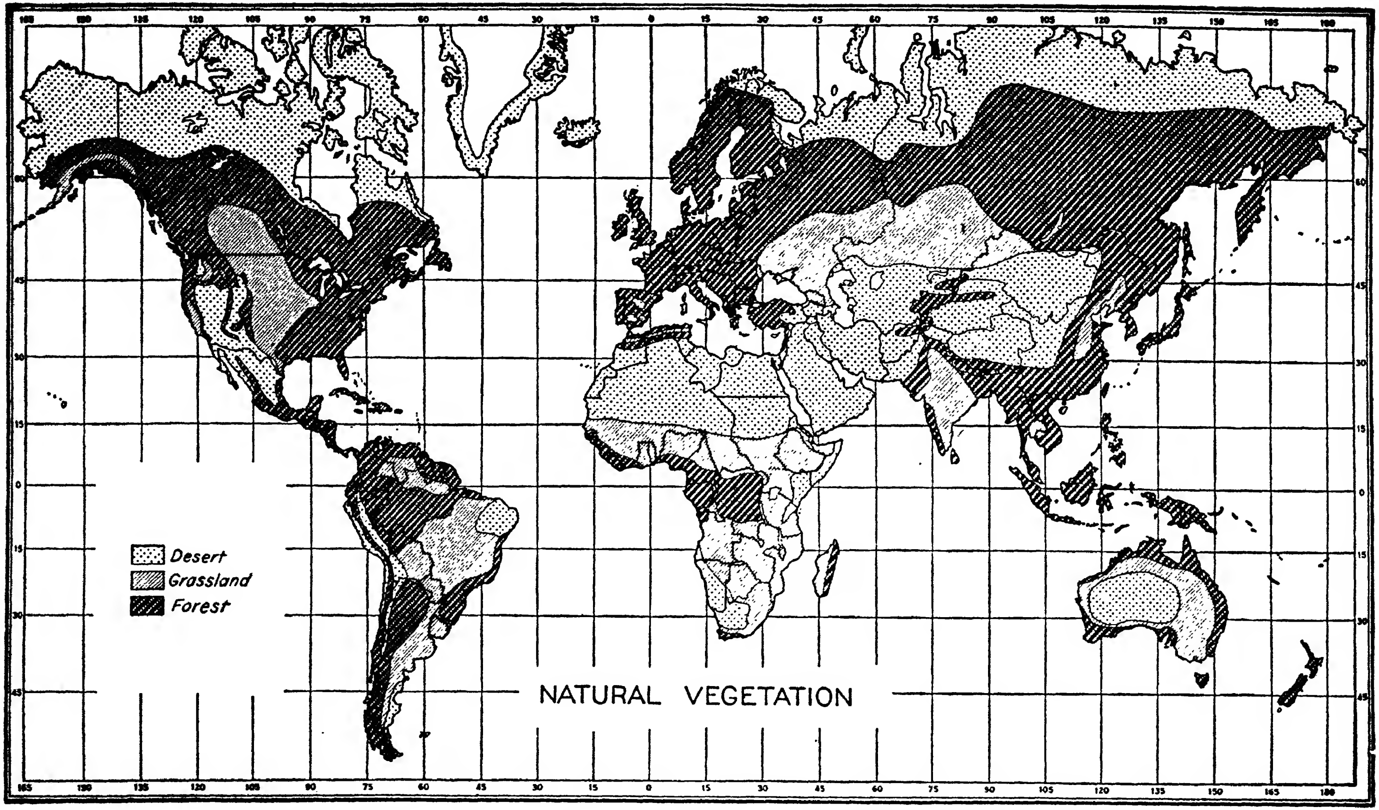


FIG. 50. Generalized world distribution of the three major divisions of the natural vegetation. (After Henry *et al.*)

and especially pines have more or less xerophilous leaves and consequently transpire less water. On the other hand, trees have well-developed root systems enabling them to draw on water supplies in the lower strata of the soil.

The seasonal distribution of precipitation is of no great consequence for the development of woodland. The important point is to have moisture in the soil and subsoil. Trees growing in areas lacking summer precipitation draw on the moisture stored in the soil in winter or in early spring. Trees are found, even in close formations, in areas with both uniform and highly periodic distributions of precipitation.

The water-vapor content of the atmosphere is important for the growth of trees. Their transpiring surfaces extend into the higher and also drier atmosphere. Large hydrophilous trees in full leaf demand, according to Schimper (16), an average relative humidity of around 80 per cent, which may drop down to 60 per cent only for a few hours during the day. Xerophilous trees are satisfied with less atmospheric humidity. Several species can withstand, even when in full foliage, a relative humidity of 30 per cent for a time without damage.

In the higher latitudes drying winds during the winter season are highly detrimental to tree growth even to the extent of excluding them under those conditions. Consequently the winters of the woodland climates have relatively moist atmospheres, and drying winds are infrequent. Drying winds during winter set the polar limits for tree growth probably as much as extremely low temperatures.

The outstanding characteristics of a woodland climate are summarized by Schimper as: A warm period of vegetation, constantly moist subsoil, and moist, still air especially during the winter.

From the above it is evident that the so-called woodland climates cover a wide range, and that they delineate only a very general condition. The main shortcoming, as far as designating definite climatic conditions to be used for comparative purposes, is that no indication is given of the seasonal distribution of precipitation. Areas with a natural cover of the hydrophilous deciduous trees have, however, under most conditions relatively humid types of climates with a fairly uniform distribution of rainfall during the

growing season. Furthermore, since these trees demand a high relative humidity of the atmosphere, the evaporation rates in their areas of growth are low while the effectiveness of precipitation is high. For this reason areas with woodland climates are adapted to crops requiring relatively moist conditions. This is true especially for areas in the middle and higher latitudes with a climax of broad-leaved deciduous trees. The main crops of the woodland areas are: the cereals, corn, potatoes, sugar beets, peas, beans, tobacco, cotton, and sugar cane. These areas grow soft wheats as contrasted to the hard, high-protein wheats produced in the drier grassland areas.

Savanna and Forest-Steppe Climates. Savannas and forest steppes represent the transitional zone between the woodlands and the true grasslands. Hayek differentiates between the true savanna and the savanna forests, the latter being found in India as a transition between the monsoon forests and the true savanna.

Savannas represent the transition between the tropical rain forests and the grasslands, and chaparral deserts in the lower latitudes. The climates are intermediate between those of the true grasslands and woodlands. In areas where the temperature is not too high they represent some of the most usable areas for agricultural purposes in the tropics. Because of the generally high prevailing temperature and a high saturation deficit of the air, however, the efficiency of precipitation is low and the climate is highly hazardous. The savannas and grasslands of Africa comprise around one-fifth of the area of that continent. Owing to the critical fluctuations in rainfall, Renner (14) refers to the savanna and grassland areas of the Sudan and adjoining Nigeria as the famine zone of Africa.

In the higher latitudes the true woodlands merge into the grasslands through a transition of parklike areas referred to by Funk (2) as forest steppes (Waldsteppen). As in the savanna the trees grow in open or scattered formations with grass in between them. These areas are of great agricultural importance. The climates are more humid and less variable than those of the true grasslands. Owing to the limited or complete absence of leaching, the soils of the forest steppe are generally more fertile than those of the humid woodlands. This in part compensates for the greater fluctuations in rainfall.

Grassland Climates. The outstanding characteristics of a grassland climate are essentially those features unfavorable to the establishment of forests, namely, limited precipitation and cold drying winds during the winter season.

In discussing the characteristics of the climates of grassland areas it is necessary to distinguish between areas with a dense or closed and those with an open or bunch-grass formation. The former are the more widely distributed and are the ones generally referred to in discussions of conditions on the grasslands. They may be called the true grasslands.

The main elements of the true grassland climates are: precipitation limited, but abundant enough to keep the surface layers of the soil moist during late spring and early summer; moderate temperatures during the period of vegetative growth, followed by high temperatures during the middle and later portions of summer; dry conditions and even severe droughts after early summer and during the autumn months; and cold drying winds during the winter. Grassland climates have a decided continental aspect. These conditions are very effective in preventing the establishment and the growth of trees. Trees are able to gain a foothold only in areas where a sufficient moisture supply is available, as along streams and in places protected from the main force of drying winds during the cold season. The same conditions also set the northern boundaries of autumn-sown cereals in accordance with their respective degrees of winter-hardiness. As stated by Weaver and Himmel (25), "water-content of soil and humidity are the master factors in the environment of the prairie."

Climatic conditions of the bunch-grass areas of the Pacific Northwest are quite different than in grass areas with close formations. The precipitation in these areas is also highly periodical, but most of it comes during the winter months. In the true grasslands from 70 to 80 per cent of the annual precipitation falls during the early portion of the growing season. Bunch-grass formations may, however, occur also within areas of the true grasslands. Here they are found in places with open soils or in sandy areas, that is, under conditions favoring the rapid penetration of practically all the water that falls.

Climatic conditions in the true grasslands are far from uniform, nor are they characterized by a uniform vegetation throughout.

The great expanses of grassland in central North America extending across the Mississippi Valley from the forests of the East to the foothills of the Rockies show great differences in luxuriance of growth, indicating great variations in climatic conditions and crop producing potentialities. As stated by Weaver and Clements (24),

> "the tall-grass prairies of the eastern portion are distinctly different from the short-grass plains of the west and southwest, and between these two regions is a broad belt of mixed grassland where tall and short grasses intermingle. The chief causes of these differences in grassland vegetation are the differences in the quantities of soil moisture supplied by the rainfall and the length of time during which soil moisture is available. Decreased relative humidity westward is also an important factor. Differences in soil structure, resulting from differences in climate and vegetation during its development, are also pronounced."

Not only do the climates become more arid in going from the tall-grass prairies to the short-grass plains, the true steppes, but they also become more variable.

The tall-grass prairie covers approximately one-third of the Dakotas, Nebraska, Kansas, and large areas in central Oklahoma. The mixed prairie occupies central Nebraska and Kansas and practically the entire remaining northern and western portion of the Great Plains area. The short-grass plains extend from western Nebraska, Kansas, and Oklahoma to the Rockies in Colorado and northern New Mexico down to northwestern Texas.

Not all areas originally covered by grasses have grassland climates. Thus in the more humid eastern portions of the grasslands of the United States, that is, in Illinois, Iowa, and Missouri, grasses occupied potential forest lands. Present as well as past soil conditions, especially in relation to drainage features, fires, and perhaps other causes, have delayed the development of the forest climax. Funk points out these same conditions for the more humid grassland areas in Europe and particularly in Russia.

Weaver (23) discusses some of the ecological aspects of agriculture in the prairie. The following paragraph from his paper merits direct citation.

> "Cereal (grass) crops and certain legumes are best adapted to the grassland. Ecologically these have much in common with the native grasses. Aside from maize, practically all important crops grown in

the grassland have been introduced from regions with a similar grassland climate. Successful agriculture has been made possible and profitable only by such introductions as Durum and Turkey Red wheat, sorghums, etc. By selection and breeding, crops even better adapted to a grassland climate have been produced, and agriculture in the prairie made more certain and more profitable. The larger cereal maize, like the taller grasses, is best developed in the eastern part of the grassland, the Corn Belt extending but little beyond the tall-grass prairie. Sorghum is an excellent crop for the drier, southwest, short-grass plains. Alfalfa replaces clover as a leguminous crop in all but the best watered portions of the grassland. It exhausts the water of the subsoil so thoroughly as to introduce puzzling agronomic problems."

KÖPPEN'S CLASSIFICATION OF CLIMATES

Basis of Classification. Köppen published two classifications of the climates of the world. The first (10) appeared in 1900, the second (11) in 1918. The more recent classification is also discussed in detail in Köppen's book *Die Klimate der Erde* (12). The early classification was based largely on vegetation zones, while the more recent one is based upon temperature, rainfall, and seasonal characteristics. These factors are of course fundamental in the distribution of vegetation. The earlier and more recent classifications show many resemblances, both in their larger climatic belts and in their smaller subdivisions. There is also a broad resemblance in the general decisive climatic features selected as the basis of the subdivisions. The discussion here and later applications to the problems of crop distribution will be limited to Köppen's more complete classification of 1918. This classification was made available to the English reader through the reviews presented by Ward (21) and James (7). Both of these reviewers reproduced Köppen's map in black and white.

Zonal Subdivisions. The fundamental zonal divisions between the equator and the poles are designated by six capital letters as follows:

A. One winterless tropical rain belt.
B. Two incomplete dry belts.
C. Two warm temperate belts without usual winter snow cover.
D. One boreal or subarctic belt with sharp distinction between summer and winter conditions (this belt does not occur in the southern hemisphere).

E. Two polar caps beyond the limits of tree growth — the tundra climate.
F. Regions of perpetual frost.

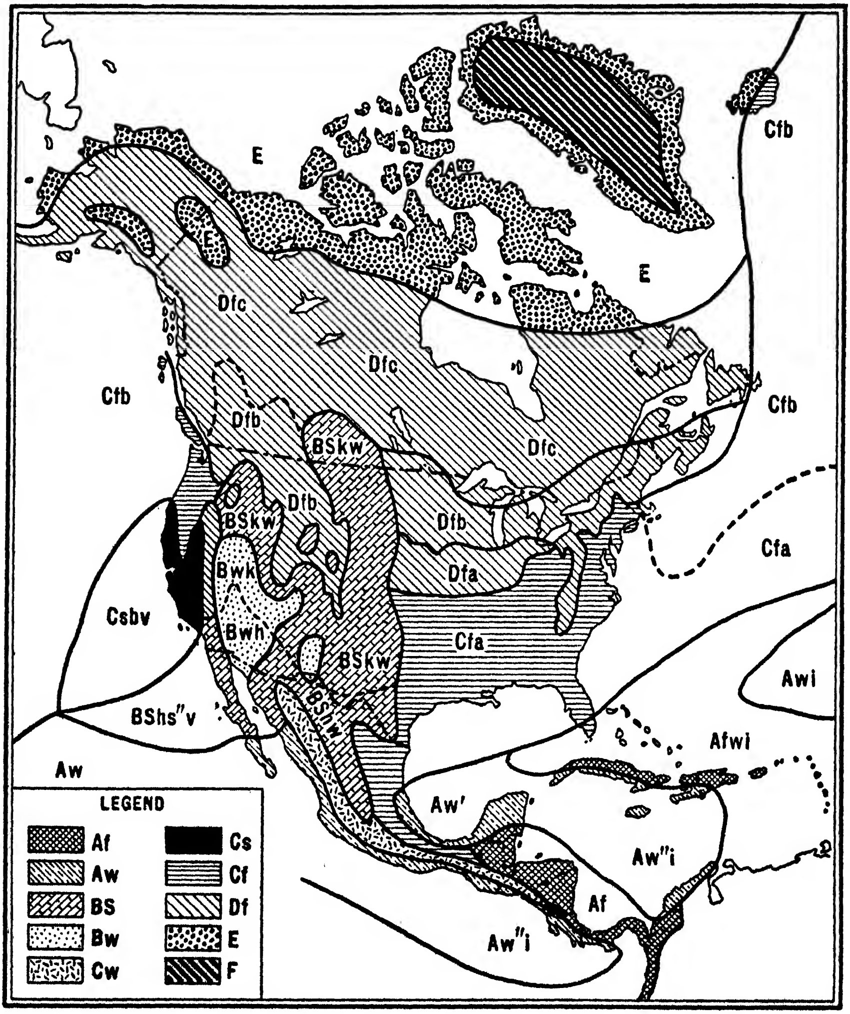


Fig. 51. Climatic regions of North America according to Köppen's classification, with modifications by Van Royen.

The first four of these zones are again subdivided on the basis of rainfall conditions. These subdivisions are given below together with the symbols employed to designate each of the types. The first letter in the formula gives the zone, it is always written in

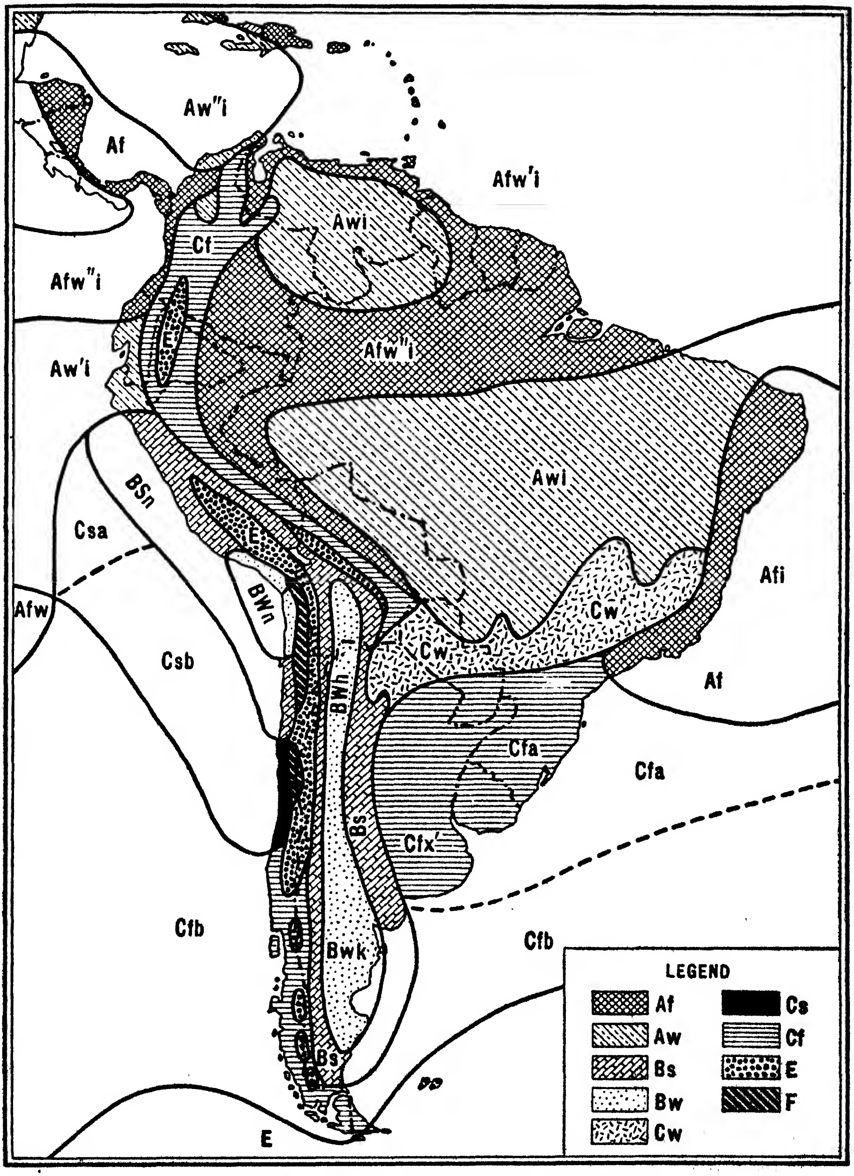


FIG. 52. Climatic regions of South America according to Köppen's classification.

capitals, also the designation of the steppe and desert climates, BS and BW.

Af — Tropical rain forest climate.
Aw — Periodically dry savanna climate.
BS — Steppe climate.
BW — Desert climate (German Wüste).

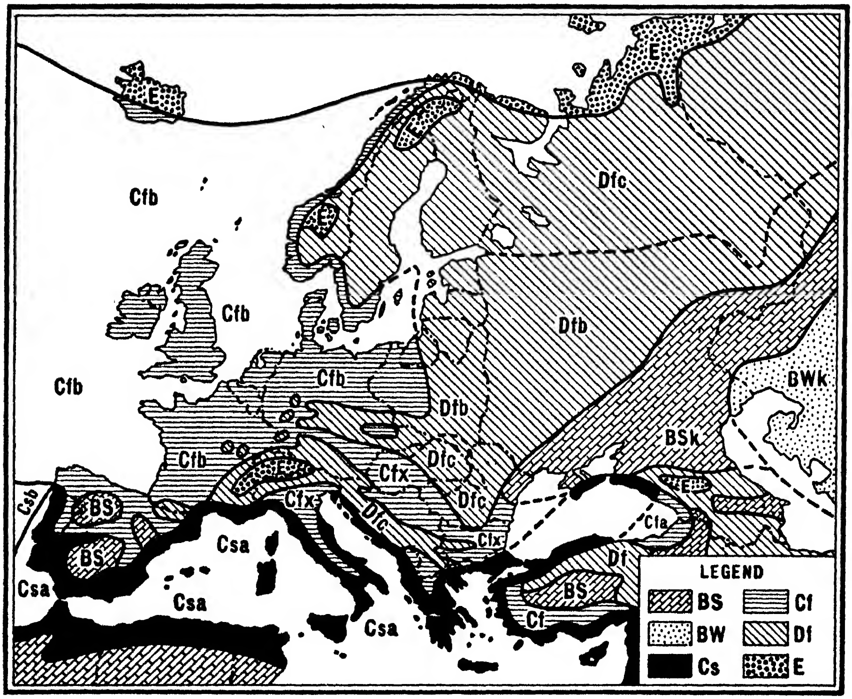


FIG. 53. Climatic regions of Europe according to Köppen's classification.

Cw — Warm climate with dry winters.
Cs — Warm climate with dry summers.
Cf — Moist temperate climate with mild winters (German feucht).
Dw — Climate with cold dry winters.
Df — Climate with cold moist winters.

Köppen's distinction between the dry, B, and the more humid, C and D, as well as that between the desert and steppe regions was discussed in Chapter XIII in connection with the determination of humidity provinces. The boundary line between the dry

and more humid climates is placed arbitrarily at the point where the annual precipitation and evaporation are in equilibrium ($P = t + y$).

Köppen also designates the temperature limits for each of the zonal types of climates. Thus in the A type the normal temperature of the coldest month of the year must be more than 18°C. In the C type the temperature of the coldest month is between

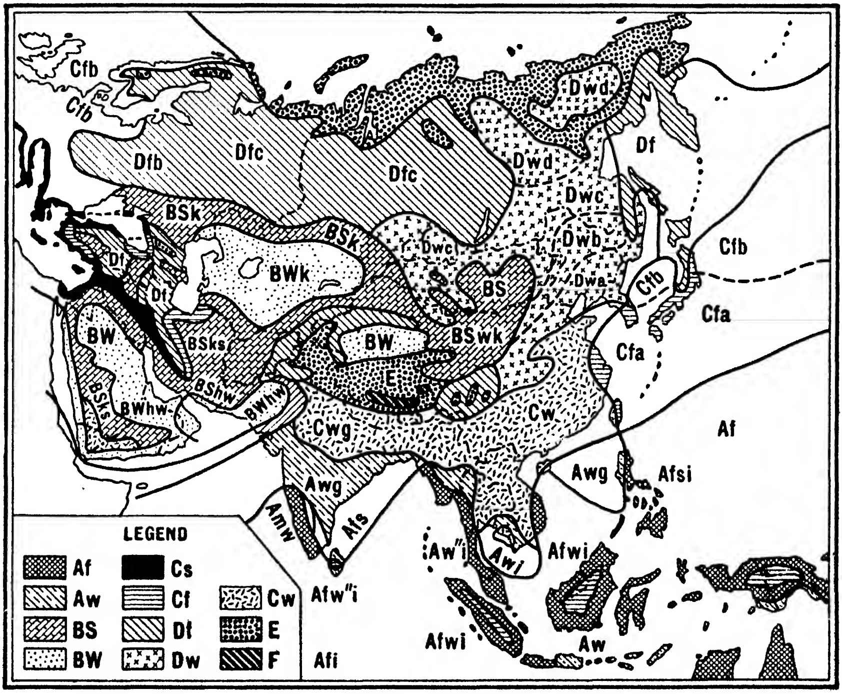


FIG. 54. Climatic regions of Asia according to Köppen's classification.

18 and − 3°C. The coldest month in the D climate is less than − 3, and the warmest month more than 10°C. In the E climates the average temperature of the warmest month is less than 10, and in the F less than 0°C.

Complete Formulation of Climatic Characteristics. In addition to the zonal subdivisions given above, Köppen enriches his map with a series of climatic symbols, indicating the variations and special developments which are found within the more general regions. This provides a complete formulation of climatic conditions. The climatic symbols are attached to the designated set of

letters for the zonal subdivisions. Thus the climatic formula Cfb indicates a moist temperate climate with mild winters with the mean temperature of the warmest month under 22°C and with

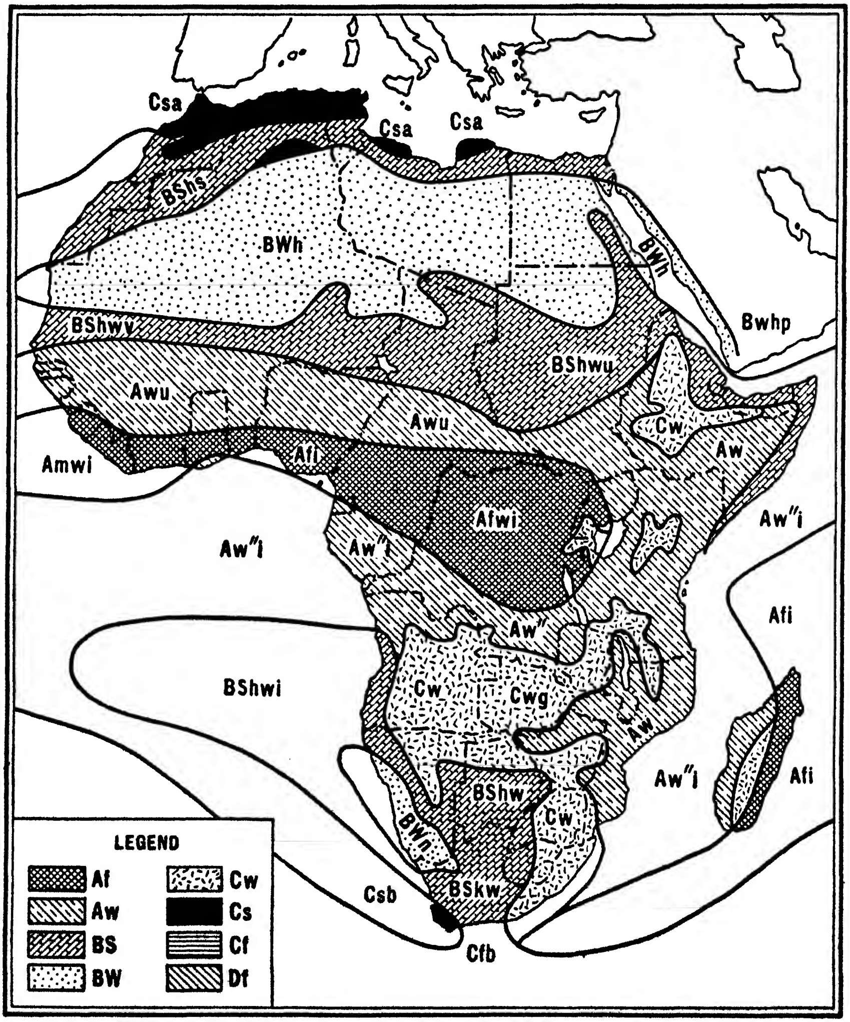


FIG. 55. Climatic regions of Africa according to Köppen's classification.

at least four months over 10°C; BSk indicates a steppe climate with cold winters, with annual temperatures below 18, and the warmest month above 18°C, etc. The symbols used are as follows, all temperature designations are on the centigrade scale.

a — Mean temperature of the warmest month above 22°.
b — Mean temperature of the warmest month under 22, at least four months above 10°.
c — Only one to four months above 10, coldest month above − 38°.
d — Temperature of the coldest month less than − 38°.
f — Constantly moist (sufficient rain or snow in all months).
g — Ganges type of annual temperature trend, with maximum before the turn of the sun and the summer rainy season.
h — Hot, annual temperature above 18°.
i — Isothermal, difference between extreme months less than 5°.
k — Cold winter, annual temperature less than 18, warmest month above 18°.
k′ — The same, but warmest month less than 18°.
l — Mild, all months 10 to 22°.
m — Monsoon rains, primeval forest in spite of one dry period.
n — Frequent fogs.
n′ — Infrequent fogs, but high humidity accompanied by lack of rainfall, and relatively cool (summer below 24°).
p — The same, with summer temperature 24 to 28°.
p′ — The same with very high temperatures (summers above 28°).
s — Driest period in summer.
w — Driest period in winter.
s′w′ — The same, but rainy season shifted into autumn.
s″w″ — The same, but rainy season in two parts, with a short dry season intervening.
u — (Reversed) Sudan type of temperature variation, with coolest month after summer solstice.
v — Cape Verde type of temperature variation with warmest season shifted into autumn.
x — Transition type with early summer rains.
x′ — The same with infrequent but intense rain at all seasons of the year.
S — Steppe climate.
W — Desert climate.

Maps of Köppen's Climatic Regions. Figures 51 to 56 give the climatic regions of the continents according to Köppen's classification. Figure 51 includes the modifications of Köppen's

original map as recommended by Van Royen (19) for the eastern portion of North America. The legends used in this set of maps correspond with modifications to those given by Passarge (13). These maps of the climatic regions of the continents together with the maps based on Thornthwaite's classification, to be discussed presently, will be referred to at intervals in Part IV; both Köppen's

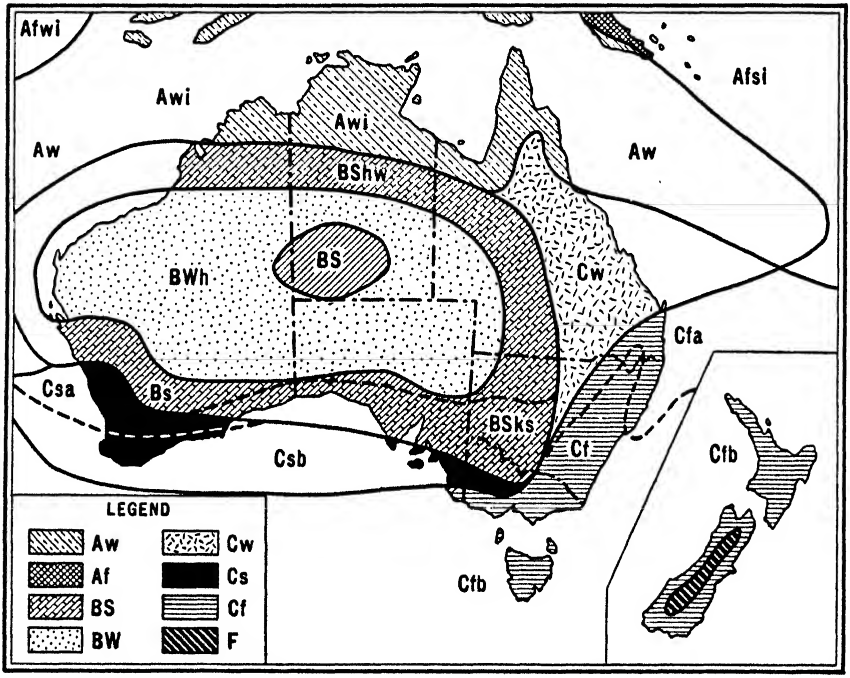


FIG. 56. Climatic regions of Australia according to Köppen's classification.

and Thornthwaite's maps are given. This will enable the checking of one against the other. These two classifications of climates have been used extensively by different investigators of climatic relationships. They will be employed in Part IV for purposes of providing a readily stated summary of the outstanding climatic features of the regions of distribution of important field crops.

THORNTHWAITE'S CLASSIFICATION OF CLIMATES

Basis of Classification. The main outstanding features of Thornthwaite's classification of climates as well as the main points of variance between this classification and Köppen's are well stated by Thornthwaite (18) in the following paragraph.

"The present classification is like Köppen's in that it is quantitative and attempts to determine the critical climatic limits significant to the distribution of vegetation and also in that it employs a symbolic

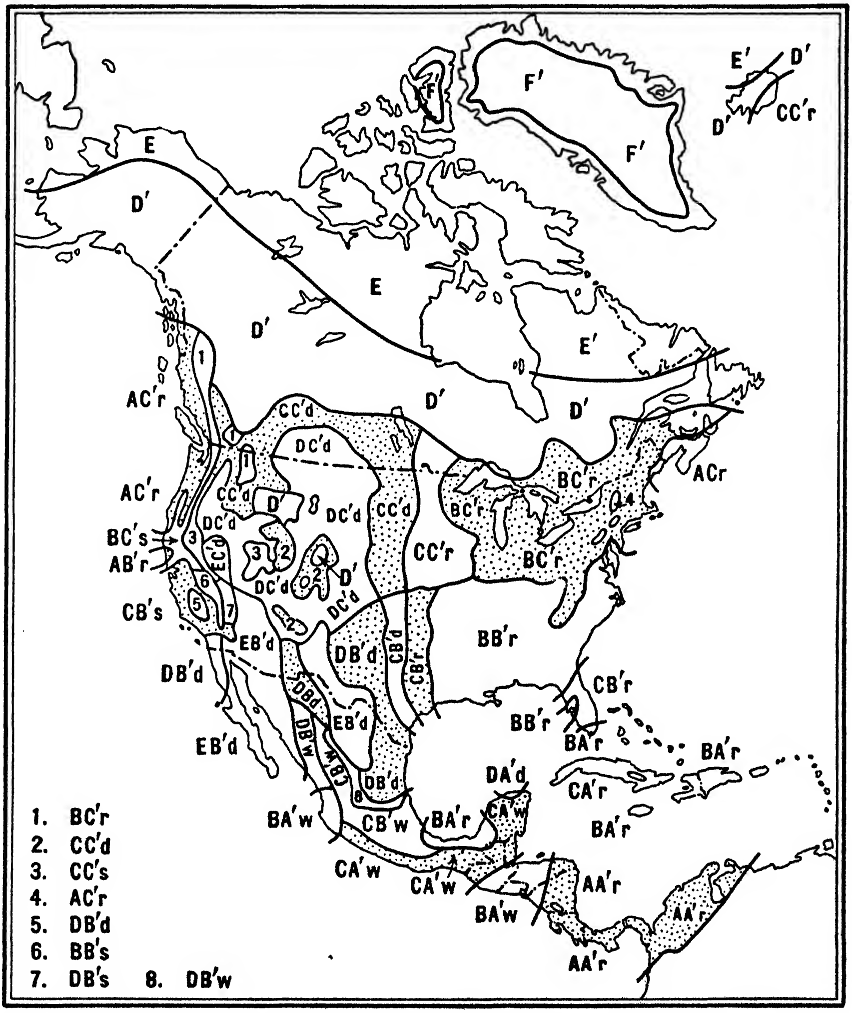


FIG. 57. Climatic regions of North America according to Thornthwaite's classification.

nomenclature in designating the climatic types. It differs from Köppen's classification in that it makes use of two new climatic concepts, precipitation effectiveness and temperature efficiency. It is inferred that in the tropical rain forest, the most rapidly growing and the densest vegetation type on the earth, the climate must be the most

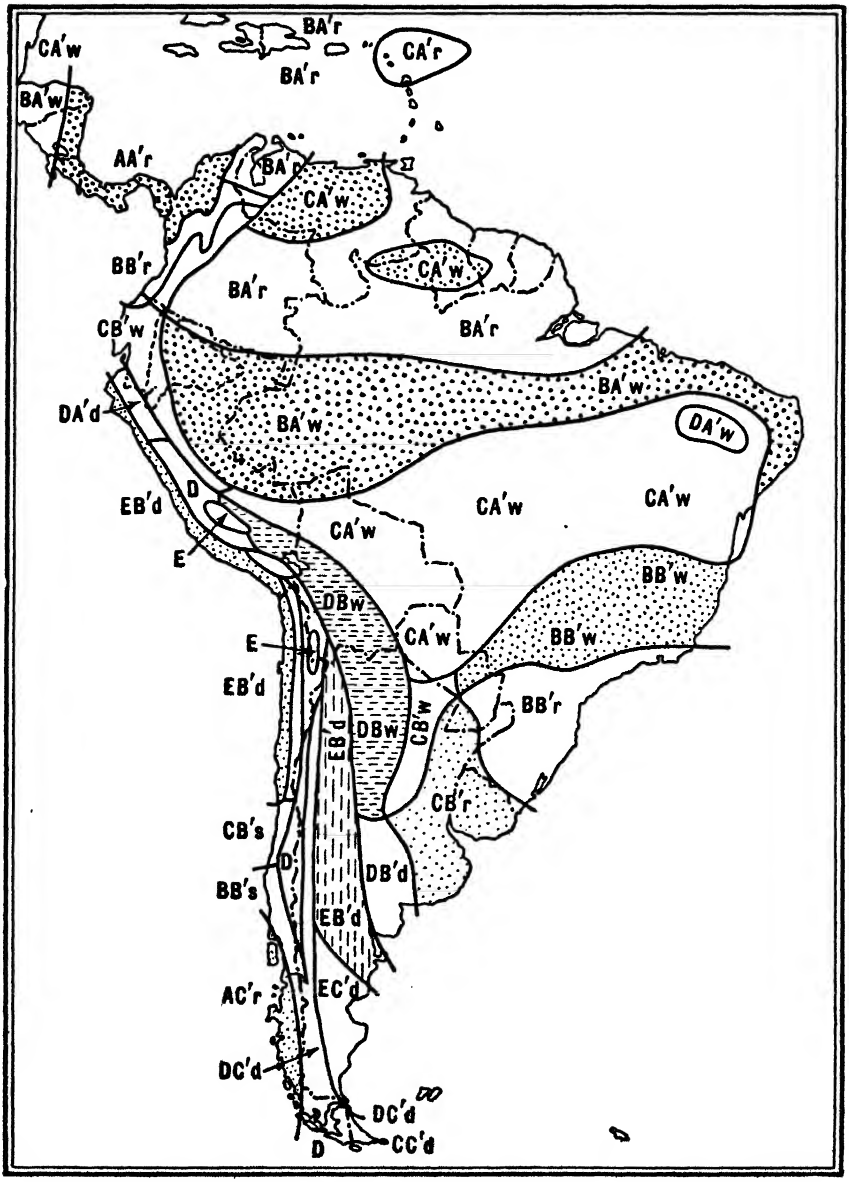


FIG. 58. Climatic regions of South America according to Thornthwaite's classification.

favorable of all for plant growth. Temperatures are constantly high and rainfall is constantly abundant. Here, therefore, the precipitation effectiveness and the temperature efficiency must be at a maximum. Diminution of either element will produce conditions less favorable for the rapid development of vegetation. It is evident that precipitation effectiveness grades from a maximum in the tropical rain forest to a minimum approaching zero in the tropical desert and that temperature efficiency grades from a maximum in the tropical climate to

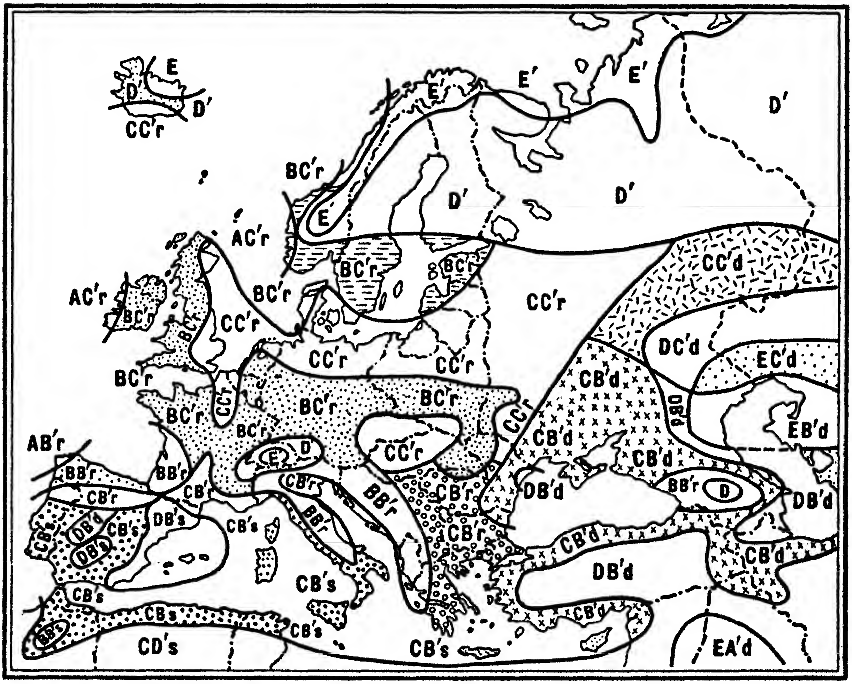


Fig. 59. Climatic regions of Europe according to Thornthwaite's classification.

a minimum at zero in the climate of perpetual frost. The vegetation transitions due to diminished effective rainfall are: (A) rain forest, (B) forest, (C) grassland, (D) steppe, (E) desert, and those due to diminished temperature efficiency are: (A′) tropical rain forest, (B′) temperate rain forest, (C′) microthermal rain forest, (D′) taiga, (E′) tundra, (F′) perpetual frost (no vegetation). The dry or cold boundaries of any of these regions are critical climatic limits beyond which the vegetation type cannot go. Of course it is understood that because of edaphic, cultural, or historical factors vegetation types do not always extend out to their climatic limits."

The boundaries of Thornthwaite's five humidity and six temperature provinces have already been discussed in their respective places in Chapters XIII and XVII.

When five humidity and six thermal zones or provinces are combined, 30 theoretical possible climatic regions result. In addition, seasonal distribution of effective precipitation was considered on the basis of abundance of: precipitation at all seasons,

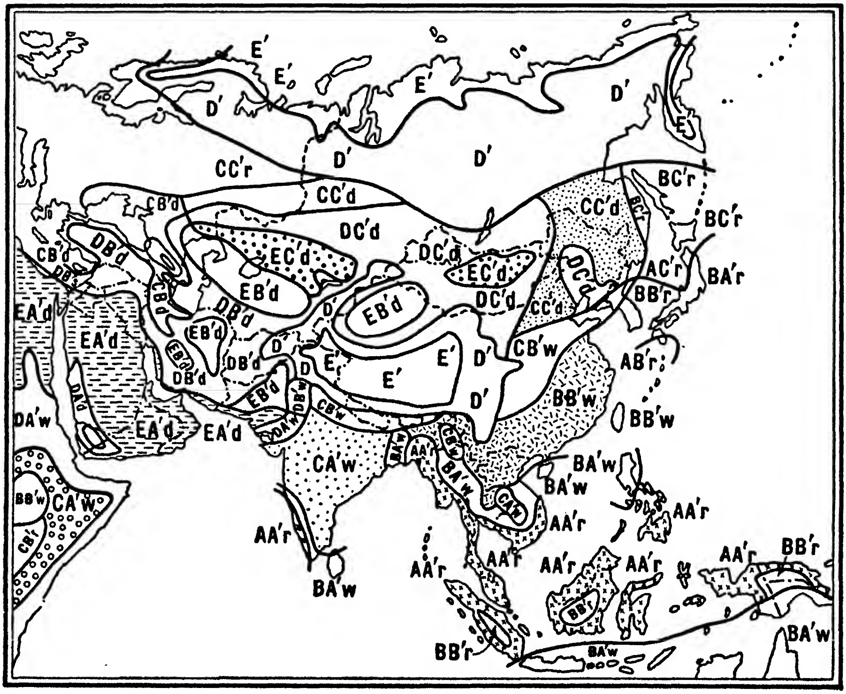


FIG. 60. Climatic regions of Asia according to Thornthwaite's classification.

the "r" type; scanty rainfall in summer (abundant in winter), the "s" type; scanty rainfall in winter (abundant in summer), the "w" type; and scanty precipitation at all seasons, the "d" type. A modification of the winter dry or "w" type is recognized in certain tropical areas. "Here the drought occurs in spring instead of winter, and the rainy season is in fall instead of summer." The type is designated as "w′."

Thus, the classification is based on three climatic factors: (*a*) precipitation effectiveness, (*b*) temperature efficiency, and (*c*) seasonal distribution of effective precipitation.

Formulation of Climatic Characteristics. The factors employed in Thornthwaite's classification have five, six, and four aspects respectively. Each is designated by a symbol. The formula

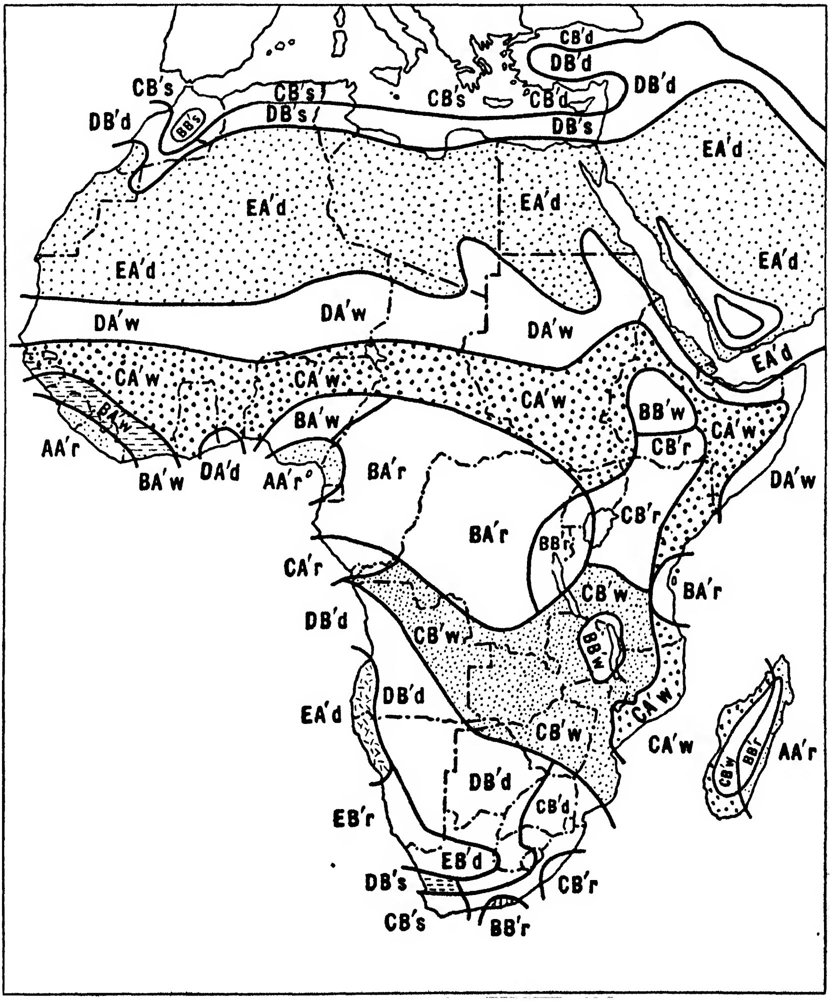


FIG. 61. Climatic regions of Africa according to Thornthwaite's classification.

for a particular climate is then designated by three combined letters, except for the D′, E′, and F′ types designating strictly temperature conditions, namely taiga, tundra, and perpetual frost, respectively. "There are 120 different possible combinations of these 15 symbols, making 120 theoretically possible climates.

However, certain combinations of symbols are eliminated by definition; and others, being meteorologically impossible, do not occur anywhere on the earth, so that of the 120 possible combinations only 32 represent actual climatic types."

In the formulation of any climatic type the humidity conditions are stated first in the form of capital letters for the respective five

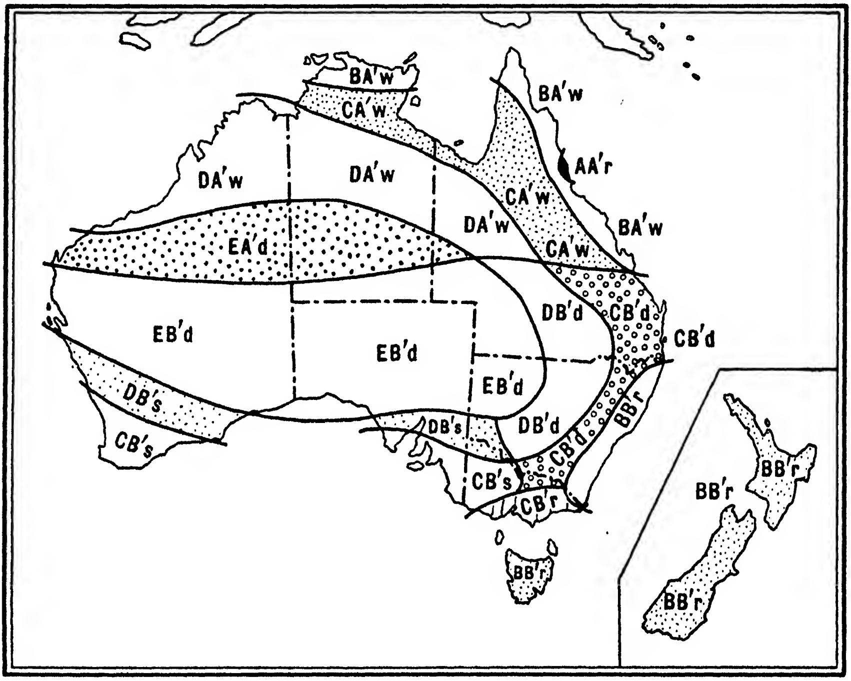


FIG. 62. Climatic regions of Australia according to Thornthwaite's classification.

types (from A to E). The second letter of the formula, also capitalized and graced with a prime mark, represents one of the six possible temperature efficiency types (from A′ to F′). The third letter of the formula represents the seasonal distribution of effective precipitation (r, s, w, d); it is designated by a small letter. Thus, a climate BB′r is humid, mesothermal (has a relatively high annual temperature), and has abundant precipitation at all seasons; a DC′d climate is semiarid, microthermal (relatively low temperatures), and has scanty rainfall at all seasons.

A fourth letter designating the summer concentration of temperatures may be used in the study of local climatic relations. Thorn-

thwaite omitted the fourth letter on his maps of the climates of North America and of the earth. Jones and Bellaire (8) found the fourth letter of value in the study of the climates of Hawaii.

Maps of Thornthwaite's Climatic Regions. Thornthwaite published maps of the climates of North America (17) and of the world (18). Figures 57 to 62, reproduced from Thornthwaite's colored maps, give the climatic regions of the continents in black and white.

REFERENCES

1. Clements, F. E., *Plant Indicators.* Carnegie Inst. Publ. No. 290, Washington, 1920.
2. Funk, S., "Die Waldsteppenland-schaften, ihr Wesen und ihre Verbreitung," *Veröffentlichungen des Geographishen Instituts der Albertus-Universität zu Königsberg. Heft* 8:1–65 (1927).
3. Hann, J., *Handbuch der Klimatologie.* 3 Aufl., Engelhorn, Stuttgart, 1908.
4. ———, *Handbook of Climatology*, Part 1, "General Climatology," trans. German by R. D. Ward. Macmillan, New York, 1903.
5. Hayek, A., *Allgemeine Pflanzengeographie.* Gebrüder Borntraeger, Berlin, 1926.
6. Henry, A. J., J. B. Kincer, H. C. Frankenfield, W. R. Gregg, B. B. Smith, and E. N. Munns, "Weather and agriculture," *U. S. Dept. Agr. Yearbook*, 1924:457–558.
7. James, P. E., "Köppen's classification of climates: A review," *Mo. Wea. Rev.*, 50:69–72 (1922).
8. Jones, S. B., and R. Bellaire, "The classification of Hawaiian climates: A comparison of the Köppen and Thornthwaite systems," *Geog. Rev.*, 27:112–119 (1937).
9. Kendrew, W. G., *The Climates of the Continents.* Clarendon Press, Oxford, 1937.
10. Köppen, W., "Versuch einer Klassification der Klimate, vorzügsweise nach ihren Beziehungen zur Pflanzenwelt," *Geogr. Zeitschr.*, 6:593–611, and 657–679 (1900).
11. ———, "Klassification der Klimate nach Temperatur, Niederschlag und Jahresverlauf," *Petermann's Mitteilungen.*, 64:193–203, and 243–248 (1918).
12. ———, *Die Klimate der Erde.* Walter De Gruyter & Co., Berlin, 1923.
13. Passarge, S., *Die Grundlagen der Landschaftskunde.* L. Friedrichsen & Co., Hamburg, 1919.
14. Renner, G. T., "A famine zone in Africa: the Sudan," *Geog. Rev.*, 16:583–596 (1926).

15. Shantz, H. L., and R. Zon, *Atlas of American Agriculture*, Sec. E, Natural Vegetation. Govt. Printing Office, Washington, 1924.
16. Schimper, A. F. W., *Plant Geography upon a Physiological Basis*, trans. German by W. R. Fisher. Clarendon Press, Oxford, 1903.
17. Thornthwaite, C. W., "The climates of North America according to a new classification," *Geog. Rev.*, 21:633–655 (1931).
18. ———, "The climates of the earth," *Geog. Rev.*, 28:433–440 (1933).
19. Van Royen, W., "The climatic regions of North America," *Mo. Wea. Rev.*, 55:315–319 (1927).
20. Visher, S. S., *Climatic Laws*. Wiley, New York, 1924.
21. Ward, R. DeC., "A new classification of climates," *Geog. Rev.*, 8:188–191 (1919).
22. ———, *The Climates of the United States*. Ginn, Boston, 1925.
23. Weaver, J. E., "Some ecological aspects of agriculture in the prairie," *Ecology*, 8:1–17 (1927).
24. ———, and F. E. Clements, *Plant Ecology*. McGraw-Hill, New York, 1929.
25. ———, and W. J. Himmel, "The environment of the prairie." *Conserv. Dept. of Conserv. and Surv. Div. of the Univ. of Nebr., Bull.* 5, 1931.

Chapter XXI

EDAPHIC AND PHYSIOGRAPHIC FACTORS

THE EDAPHIC FACTORS

Introduction. The treatment of as broad a topic as the edaphic and physiographic factors of the environment demands a statement. The scope of such a title is so comprehensive that it cannot be treated in detail within the confines of one chapter. Only some of its more important aspects can be pointed out. Various phases of the soil factor have been discussed in previous chapters in connection with their respective interrelationships with the other factors of the environment. The student interested in specific phases of the soil and physiographic factors as they relate to crop and soil studies of necessity must consult the extensive and highly specialized literature available on these important topics.

The Nature of Soil. The soil is not a static body but should be regarded as a living and highly dynamic entity with natural provisions for continued development and renewal. Soil differs from parent material entering into its formation in color, structure, texture, physical constitution, chemical composition, biological characteristics, probably in chemical process, in reaction, and in morphology.

In relation to its genesis and the development of its characteristics, soil is regarded by Kellogg (7) as a function of climate, vegetation, relief, age, and parent material.

Major Soil Groups. The development of the two major groups of soils, the pedocals or lime-accumulating, and the pedalfers or nonlime-accumulating, was discussed in connection with the moisture factor of the environment, Chapter XI. It was logical to discuss the major soil groups at that point, since existing moisture and temperature conditions together with the closely associated vegetative features account for the development of the characteristics differentiating them. They are mentioned here for the sake

of completeness. Figure 63, taken from Kellogg (7), shows the dividing line between these two major soil groups in the United States. It will be observed that the pedalfers are found in the humid, and the pedocals in the semihumid and arid sections of the country.

Zonal Groups of Soils. Zonal soils are found over large areas or zones, limited by geographical features. Their well-developed

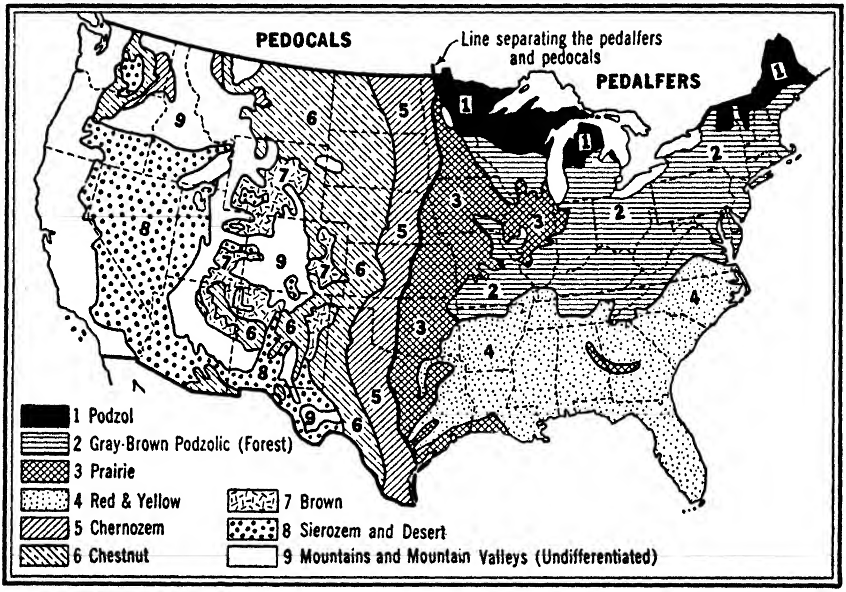


FIG. 63. General distribution of the important zonal groups of soils in the United States. (After Kellogg [7].)

soil characteristics indicate that their parent materials have been in place and exposed to the factors of soil genesis and especially to the climatic and biological factors long enough to have expressed their full influence.

The zonal groups of soils constitute rather large units. They are classified on the basis of their outstanding and fundamental characteristics which differentiate them. Figure 63, taken from Kellogg (7), gives the general distribution of the important zonal groups of soils in the United States. Figure 64, also taken from Kellogg (8), gives a schematic map of the primary groups of soils in the world. This map is compiled from materials presented by Glinka, Marbut, and others. The close agreement between

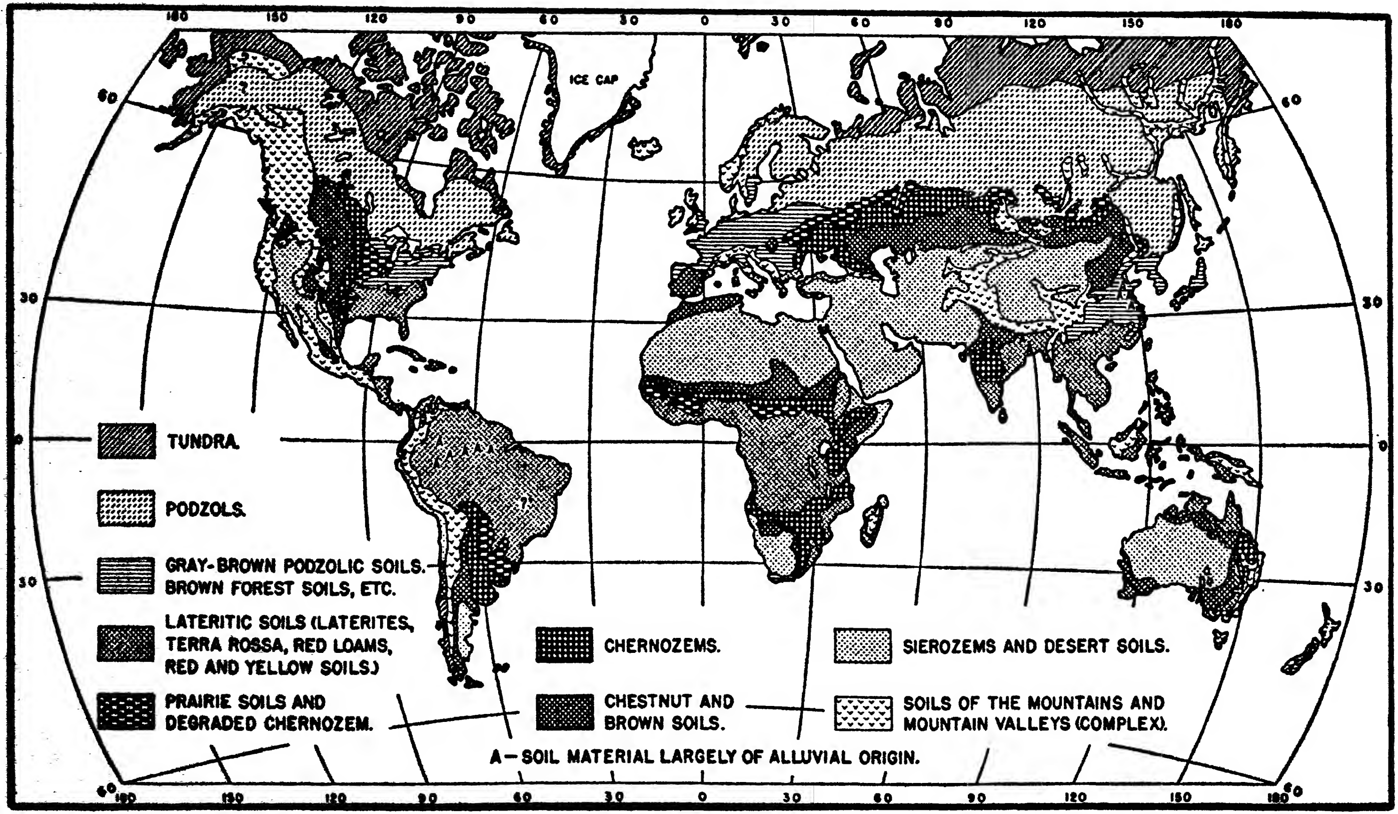


Fig. 64. Schematic map of the primary groups of soils of the world. (After Kellogg [8].)

these maps and maps showing vegetation types is quite evident. The outstanding characteristics of the profiles, the native vegetation, climate, soil-development processes, the natural fertility, and the dominant agricultural utilizations of the zonal and intrazonal groups of soils are given by Kellogg (7) and by Baldwin *et al.* (1).

Physical Aspects of the Soil. The physical properties of a soil may be approached from the standpoint of its texture and structure. The depth of the soil also is of great importance to its economic utilization. The close relationship of these factors to the water economy of plants is evident in that they determine both the ease with which water may penetrate and the amount of water the soil is capable of holding. Their effects, however, are more extensive than that. They also are associated definitely with the chemical status of the soil, influence microbiological activities, and, aside from the water factor, determine largely the extent of root penetration. In connection with the depth of the water table they determine the sanitary conditions of the soil. The soil horizons constitute an important and conspicuous part of the physical aspects of the soil. Localized ecological studies demand a close examination of the soil profile. Differences in crop responses often can be accounted for by differences in the soil environment of the various horizons.

Chemical Aspects of the Soil. The main points of importance under this heading are the fertility relationships in the soil. Soil reactions will be discussed under a separate heading.

It is not necessary to discuss here the various elements, both major and minor, required for normal plant growth. Deficiencies of plant nutrients and lack of proper balance between the essential elements have decided depressing effects on crop yield. An abundant supply of nutrients is especially important during the grand period of growth. Deficiencies may be and often are supplied to meet specific requirements, either by the inclusion of such crops as legumes or green manure crops in the course of the rotation or by means of commercial fertilizers. The need for and the economy of such applications are determined by the state of fertility of the soil, by the existence of certain deficiencies, by climatic conditions, and by the degree of intensity of production demanded by the social factors of the environment.

The nitrogen content of a soil is more or less associated with its

fertility. The various factors entering into soil genesis, especially the climatic and temperature factors, come definitely into play in determining the nitrogen level of soils in various areas. The relative availability of nitrogen determines not only the type and luxuriance of the vegetation produced but also its rate of decomposition upon its return to the soil. Thus, Jenny (5) points out that the nitrogen content of soils decreases exponentially within regions of equal moisture and corresponding vegetations with increasing temperatures. The carbon contents of oils is influenced by the factors affecting nitrogen. The carbon-nitrogen ratio is of great importance in soil fertility investigations. Not only do the carbon and nitrogen contents of soils decrease with increasing temperatures, but the carbon-nitrogen ratio becomes wider in going from a southern to a northern area. The rate of decomposition of organic materials increases rapidly, within limits, with increasing temperatures. Jenny points out a possible limit to this relationship by calling attention to the fact that "very high temperatures retard the decomposition velocity of organic matter content, the possibility exists that in tropical regions the nitrogen and organic matter content (including the C : N.ratio) increase again, in other words, the nitrogen temperature relation may also have a minimum."

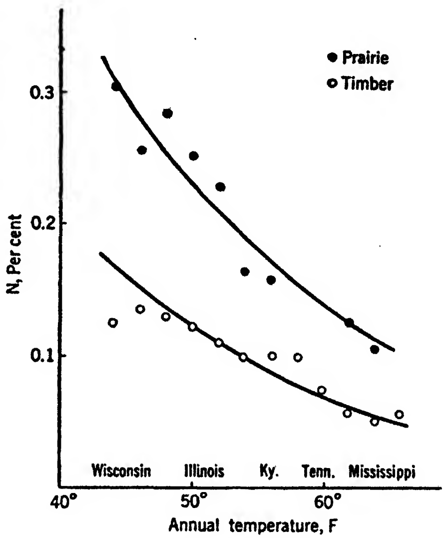


FIG. 65. Nitrogen-temperature relation in humid prairie (upper curve) and humid timber soils (lower curve) for silt loams. (After Jenny.)

The nitrogen-temperature relation for silt loams in the humid prairie and humid timber soils of the United States is shown in Fig. 65, taken from Jenny.

On account of the limited plant growth, the nitrogen contents of desert soils are low even under low temperature conditions. Within the same temperature province the nitrogen contents of

soils increase logarithmically with increases in the humidity factor. Jenny comes to the conclusion that the nitrogen content of loamy grassland soils in the United States and no doubt in other sections of the world is a function of the annual temperature and annual humidity factors.

When a virgin soil is used for crop production the nitrogen content decreases. The rate of decrease is dependent on the system of cropping instituted. Under high temperature conditions it will be found difficult and even impossible to restore the nitrogen and organic matter to its virgin level. With the use of a good system of cropping, that is, a system allowing for the liberal additions of crop residues, green manures, farm manures, and the use of legumes in the rotation, it is possible to build up or at least maintain the nitrogen and organic matter contents in northern areas. In southern latitudes, and even in the middle latitudes, the high rate of decomposition of organic materials under high temperatures makes it difficult, or even impossible, to increase the nitrogen contents of cultivated soils permanently or profitably. This condition, together with the fact that these soils were originally low in nitrogen, no doubt provides one of the reasons for the extensive use of commercial nitrate fertilizer in the southeastern portion of the United States. A sufficient supply of nitrogen to satisfy the requirements of the current crop grown is supplied without attempting to build up the total amount in the soil. Nitrogen is readily lost from the soil by leaching. Under conditions of high rainfall and high temperatures, it is difficult to build up the supply of this element in the soil.

Soil Nitrogen-Climate Relation and Corn Yields. Yields of corn as well as yields of any other crop are dependent on both the climatic and the edaphic factors of the environment. The foregoing discussion of the nitrogen-climate relation indicates that this may be of considerable importance in determining the effectiveness of the edaphic factor. Jenny has shown this to be the case.

Figure 66, taken from Jenny's paper, shows the average corn yield and soil nitrogen curves from eastern North Dakota, and the states of Minnesota, Iowa, Missouri, Arkansas, and Louisiana. A decided parallelism between the nitrogen content of the soil and corn yields is clearly evident. The downward trend of the corn yields from central Iowa to Louisiana follows closely the trend of

the soil nitrogen curves. North of central Iowa low prevailing temperatures apparently overwhelm the beneficial effects of higher soil fertility as evaluated by soil nitrogen, and the yields decrease.

Climatic conditions in the South are generally favorable to corn production. Soil factors and especially low soil nitrogen content constitute the main limiting factors to the attainment of high yields. In this connection Wallace and Bressman (10) state, "The cotton states would undoubtedly be another Corn Belt if the soil were only richer. As it is, nearly all the records of corn yielding over 200 bushels per acre have come from the South, such results being obtained by planting corn thickly on land heavily fertilized."

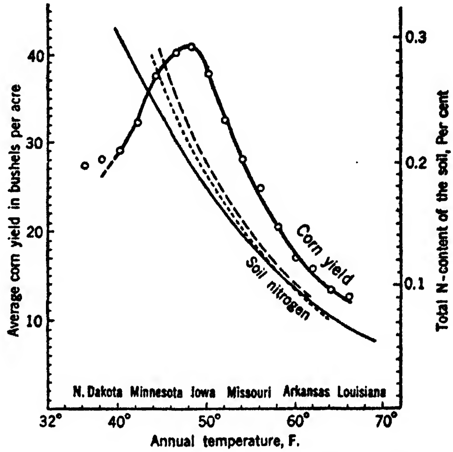


FIG. 66. Average corn yield per acre and average soil nitrogen as a function of annual temperature. In the soil nitrogen curves the solid line represents the total nitrogen content of upland prairie soils, the dotted line, that of terrace (timber) soils, and the line presented in dashes, that of bottom (timber) soils. (After Jenny.)

Soil Reaction. The majority of plants of agricultural importance grow best in soils with approximately neutral reactions. While certain plants show a high degree of tolerance, any great deviation from the neutral point will result in either direct or indirect detrimental effects. If the deviations are very great, either on the acid or the alkaline side, direct toxic or destructive effects to plant tissues will be evident. Another direct effect on plants results from the unfavorable balance between the acidic and basic constituents of the soil solutions. This balance is directly influenced by soil reaction.

The indirect effects are many. The most outstanding are the changes induced in the physical, more particularly the structural, relationships. In acid clay soils a supply of calcium bicarbonate in the soil solution insufficient to keep the base exchange material well saturated with calcium leads to the establishment of the undesirable deflocculated condition of the soil with its complica-

tions of poor tilth, poor aeration, and low chemical and microbiological activity. Highly acid or highly alkaline conditions, by inducing dispersion of colloidal particles, may lead to the development of detrimental hardpans by creating conditions favoring the downward movement of these fine particles of the soil into the subsoil where they may be precipitated. Such conditions materially interfere not only with the percolation of moisture, but also with the penetration of the roots. "The availability of all of the essential elements obtained by plants from the soil," states Truog (9), "is affected in one way or another by the reaction of the soil. Phosphorus in particular becomes less available as the *p*H value drops below 6.5 to points of greater acidity." The high calcium content found in certain alkaline soils also may interfere with the availability of this element.

There are various designations for soil acidity. Generally it is expressed in terms of *p*H values. Thus, in a glossary of special terms in the *United States Department of Agriculture Yearbook* of 1938 an acid soil is defined as: "A soil giving an acid reaction (precisely, below *p*H 7.0; practically, below *p*H 6.6) throughout most or all of the portion occupied by roots. More technically, a soil having a preponderance of hydrogen ions over hydroxyl ions in the solution." Likewise, an alkaline soil is defined as: "Any soil that is alkaline in reaction. (Precisely, above *p*H 7.0; practically, above *p*H 7.3.)"

The direct effect of climatic factors and especially of the moisture factor in the development of either acid or alkaline soil conditions is evident from the above definitions. In the development of acid soils the soluble bases are removed by conditions of high rainfall and the resulting leaching processes, while alkaline conditions are accounted for by precisely the lack of leaching during the weathering of the parent material. Contributing factors in the development of acid soils are the organic acids produced by plants, the low base content of residual materials added to the soil, and the character of their decomposition. The development of alkaline conditions is aggravated by impeded drainage, seepage, and high rates of evaporation. In the case of soils with alkaline reactions the specific effects of the salts involved play an important part in the utilization of these soils. Generally alkaline soils are classified as solonchak and solonetz soils. In the solonchak soils, also desig-

nated as white alkali soils, the salts most frequently encountered are the chlorides and sulphates of sodium and calcium and less frequently those of magnesium and potash salts. The nitrates usually produce a brown color and are referred to for that reason as brown alkalies. Alkali-claypan soils are known as solonetz. They are formed under conditions of low calcium and high sodium content of the soil. With the removal of the soluble salts the sodium clays hydrolyze and deflocculate the colloidal particles; as a result the soil becomes sticky, jellylike, and impermeable to water. The salts concerned in this are chiefly the carbonates of sodium and potassium. In the course of the deflocculation of the clays the soil organic matter may be dispersed, giving the soil mass a dark-brown or black color. This accounts for the commonly used terminology of black alkali.

TABLE 18. CROPS GROUPED ACCORDING TO THEIR TOLERANCE TO ACIDITY (after Jones)

Very Sensitive to Acidity	*Will tolerate some acidity, but are usually helped by liming. These crops are not injured by liming unless excessive applications are made*		*Strong Acidity Favorable*
	Will tolerate slight acidity	Will tolerate moderate acidity	
Alfalfa	Red clover	Soybean	Blueberry
Sweet clover	Mammoth clover	Vetch	Cranberry
Barley	Alsike clover	Oats	Holly
Sugar beet	White clover	Rye	Rhododendron
Cabbage	Timothy	Buckwheat	Azalea
Cauliflower	Kentucky bluegrass	Millet	
Lettuce	Corn	Sudan grass	
Onion	Wheat	Redtop	
Spinach	Peas	Bent grasses	
Asparagus	Lima, pole, and snap beans	Tobacco	
Beets	Carrot	Potato	
Parsnip	Cucumber	Field bean	
Celery	Brussels sprouts	Parsley	
Muskmelon	Kale	Sweet potato	
Rutabaga	Kohlrabi		
	Pumpkin		
	Radish		
	Squash		
	Sweet corn		
	Tomato		
	Turnip		

Various crops differ in their tolerance of degrees of acidity and alkalinity. Thus, alfalfa and sweet clover have a suitable range of *p*H values of 6.5 to 7.5, as compared to red clover, 6.0 to 6.5, and lespedeza, 5.5 to 7.0. Table 18, taken from Jones (4), groups crops in accordance with their relative tolerance to acidity. It will be observed that the perennial and biennial legumes are either very sensitive to acidity or will tolerate only slight acidity. This fact emphasizes the importance of soil reaction in that these leguminous plants occupy such an important place in crop rotation systems designed to maintain the soil in a fertile condition.

TABLE 19. CROP PLANTS MOST LIKELY TO SUCCEED IN THE PRESENCE OF DIFFERENT DEGREES OF SALINITY (after Kearney and Scofield)

1. Strong salinity, 0.8 to 1.0 per cent	3. Medium salinity, 0.4 to 0.6 per cent
Sugar beets	Sweet clover
Mangels	Cotton
Strawberry clover	Asparagus
Rhodes grass	Foxtail millet
Bermuda grass	Wheat (hay crop)
Bluestem (western wheat grass)	Oats (hay crop)
Smooth brome grass	Barley (grain crop)
Tall oat grass	Rye (grain crop)
	Rice
	Sunflowers
2. Medium-strong salinity, 0.6 to 0.8 per cent	4. Weak salinity, 0.1 to 0.4 per cent
Slender wheat grass	Wheat (grain crop)
Crested wheat grass	Emmer (grain crop)
Italian rye grass	Oats (grain crop)
Meadow fescue	Grain sorghums
Rape	Proso
Kale	Alfalfa
Sorgo	Vetch
Barley (hay crop)	Horsebean
	Field peas
	Red clover

Kearney and Scofield (6) present a classification of crops on the basis of their salt tolerance. This classification is presented in Table 19. So many different salts and combinations of salts occur in saline soils that any classification of this type can be of a general nature only. As stated by these investigators, "the classification applies most closely where the predominant salts are sulphates. In localities where common salt (sodium chloride) forms the bulk

of the soluble material it will be found that most of the crop plants mentioned succeeded best at the lower limits of the respective grades. If an appreciable quantity of sodium carbonate, constituting the so-called black alkali is present, the classification will not hold good at all." The various degrees of salinity are expressed on the basis of the percentage of soluble salts by weight in a depth of soil ordinarily occupied by the roots of the plants in question. It is to be assumed that the crops are grown with good farming practices and under moisture conditions favorable to growth. The concentration of the soil solution at any given time is obviously greatly affected by the moisture content of the soil mass.

Water Relations of Soils. One of the important functions of the soil is to serve as a reservoir for the water required by plants. This involves two important considerations. First, the conditions of the surface layer as well as those of the deeper strata must allow the entrance of water. Second, the soil must have capacity to hold water for future use.

The ideal soil-water relationship is encountered when textural and structural factors, and the nature of the organic constituents of the soil, favor rapid infiltration of water and at the same time allow for a maximum storage capacity. Such a combination of conditions would tend to reduce to a minimum water losses through runoff and also through direct evaporation. A rapid rate of infiltration of water into the soil enables surface moisture to penetrate into the deeper layers where it will benefit plants and evaporate less rapidly than when held near the surface. A rapid rate of infiltration also allows the surface inches of the soil to become dry shortly after rains. This breaks the capillary connections so that the water can then leave the soil only by the slow process of evaporation from the upper capillary fringe and diffusion through the dry layer above. For this reason soils with rather sandy surfaces frequently show the effects of drought less rapidly than heavy soils that are not self-mulching.

Not all water entering the soil is available for plant use. Some of it percolates downward through the subsoil and drains away. Since it moves primarily in response to the force of gravity, this is called the gravitational water. The amount of water left in the soil after the gravitational water is removed is designated as the field capacity; this point is slightly below the maximum capillary

capacity. But again, not all of this water can be utilized by plants. Plants are able to reduce the water content of soils only to their respective wilting coefficients. The amount of water available for plant use then represents the difference between the field capacity and the wilting coefficient. The wilting coefficient of most soils corresponds fairly close to the lower limit of the capillary water. The limits to which plants can remove water from a soil depend to some extent on the crop grown but primarily on the soil and climatic factors. Briggs and Shantz (2), after considerable work with a great variety of plants, came to the conclusion that the wilting coefficient equals the hygroscopic coefficient divided by 0.68 ± 0.012. Capalungan and Murphy (3) formulate the wilting coefficient as the hygroscopic coefficient divided by 0.61 ± 0.014. The hygroscopic coefficient is referred to usually as the point when the water content of the soil is so low that the water no longer moves under the influence of capillary forces. At that point the water is held very strongly as thin films on soil grains and as minute wedges and rings at their points of contact. The amount of water thus held is closely associated with the quantity of both the inorganic and organic colloids in the soil. In fact, this relationship is so close that the amount of hygroscopic water can be taken as an index of the quantity of colloid present in the soil.

THE PHYSIOGRAPHIC FACTORS

Relationship between the Edaphic and Physiographic Factors. As brought out in Chapter VI, the physiographic factors of the environment include the nature of the geologic strata, the topography, and the altitude.

The nature of the geologic strata accounts not only for the kind of parent material utilized in soil formation but also, to a high degree, for the topography and the drainage features. All of these conditions have a direct bearing on the characteristics of the soils formed and on the proper utilization of such soils.

Topography. The advent of mechanized agricultural production has emphasized the importance of topography. Mechanized equipment can be used to best advantage on relatively level areas, unbroken by topographical barriers. It is precisely on the great relatively level expanses of the plains and floodplains that most of the world's agricultural commodities are produced. Among them

are included the plains of the Mississippi Valley, the Argentine pampas, the plains extending from the Atlantic Ocean and along the North and Baltic Seas from France into northern Russia, the Hungarian plains, the plains of southern Russia, the delta plain of the lower Nile, and the delta floodplains of India and China. Agricultural production in territories with rough topography is generally limited to livestock production and not infrequently to subsistence types of farming. A rough topography increases not only the cost of production but also the cost of marketing of the commodities produced.

Not all plains are suited to crop production. Some of them are too swampy for occupation; some have poor soils, like the sandy soils of parts of the Atlantic coastal plain; and there are some with too dry a climate, or so far north that the climate is too cold, as in northern Canada and Siberia. In the interiors of the continents many of the plains extend into minimal areas best utilized for livestock rather than for crop production. In many of these regions local areas with broken topography have been protected from unwise exploitation by the fact that their topographical features prevented the destruction of their native vegetations by an overly optimistic plowman.

Soil erosion is often a great destructive agent in areas with rolling or rough topography. This is especially the case in areas with high rainfall intensities.

Topographical features are closely related to drainage facilities, either because the slope gradient may not be sufficient to remove the excess water fast enough, or because of obstructions in the drainage channels.

Altitude. In mountainous regions altitude is the most important factor determining local climate. It influences both temperature and moisture conditions, and, as pointed out in Chapter XVIII, the characteristics of alpine plants are accounted for to a high degree by the altered light conditions. The rarefication of the atmosphere with increasing elevations also serves to increase transpiration rates of plants.

In the tropics altitude is of especial significance to the utilization of areas for agricultural purposes. The moderation of temperature and not infrequently of humidity conditions associated with increasing elevation make these areas habitable for members of

the white race. The moist tropical lowlands are unsuited for white occupation on account of the enervating effects of the climate and the danger of tropical diseases.

Physiographic and Edaphic Factors of Special Importance in Studies of Local Conditions. This topic was discussed in Chapter VI. It is mentioned here for the sake of emphasis. Climatic conditions over wide regions, except where significant differences in altitude are encountered, are more or less similar. Soil conditions, however, may and do vary considerably and at times abruptly within limited areas. This is not surprising in view of the many factors that may alter soil characteristics. It emphasizes the importance of soil and physiographic features in relation to localized ecological investigation. The thesis that climatic factors have regional effects, or are regional in their scope, while the soil factors are local in effect, is fully supported. This does not mean that the effects of the soil and climatic factors themselves are distinct and separate. They are closely related in their direct and indirect effects on plant life. As a matter of fact, plant responses in a given place are conditioned as much by one as by the other in that the climatic factors often find expression through the soil factors. The climatic factor, for instance, determines the amount of rainfall received in any given place, but the plant obtains its water and mineral elements from the soil.

REFERENCES

1. Baldwin, M., C. E. Kellogg, and J. Thorp, "Soil classification," *U. S. Dept. Agr. Yearbook* 1938:979–1001.
2. Briggs, L. F., and H. L. Shantz, "The wilting coefficient for different plants and its indirect determination," *U. S. Dept. of Agr., Bur. of Plant Ind., Bull.* 230, 1912.
3. Capalungan, A. V., and H. F. Murphy, "Wilting coefficient studies," *Jour. Amer. Soc. Agron.*, 22:842–847 (1930).
4. Jones, E., "Liming Ohio soils," *Ohio Ext. Bull.* 177, 1936.
5. Jenny, H., "A study of the influence of climate upon the nitrogen and organic matter content of the soil," *Mo. Agr. Exp. Sta. Res. Bull.* 152, 1930.
6. Kearney, T. H., and C. S. Scofield, "The choice of crops for saline land," *U. S. Dept. Agr. Circ.* 404, 1936.

7. Kellogg, C. E., "Development and significance of the great soil groups of the United States," *U. S. Dept. Agr. Misc. Pub.* 229, 1936.
8. ———, "Soil and society," *U. S. Dept. Agr. Yearbook* 1938:863–886.
9. Truog, E., "Soil acidity and liming," *U. S. Dept. Agr. Yearbook* 1938: 563–580.
10. Wallace, H. A., and E. N. Bressman, *Corn and Corn-Growing*. Wallace Pub. Co., Des Moines, 1923.

PART IV

THE GEOGRAPHICAL DISTRIBUTION OF CROP PLANTS

Chapter XXII

THE SMALL GRAIN CROPS

WHEAT

INTRODUCTORY AND HISTORICAL

Commercial Importance. Wheat and rye are the bread crops of the world. The flours of these two cereals form a dough when mixed with water which upon leavening and baking produces a porous bread. This is due to their gluten content which imprisons the carbon dioxide produced in the fermentative action of yeast. Wheat produces a lighter, more porous, and generally more palatable bread of higher net energy value than rye. It is for this reason more acceptable and widely used for the making of bread than rye. So great is the demand for wheat that rye can be considered as a substitute for wheat. Rye is made use of and assumes a place of importance in the diet only in countries or areas where soil and climatic conditions are unfavorable for wheat production. Wherever conditions favor wheat production or the economic status of a people permits the utilization of wheat the consumption of rye falls sharply behind the use of wheat bread.

While wheat has no rival as a bread crop, there is some doubt in the minds of certain investigators as to whether it is more important as a food crop than rice. In this connection Zimmermann (30) states that "the statistical data on the production and consumption of wheat and rice are so incomplete that the question as to the respective numbers of wheat and rice eaters or the relative size of wheat and rice crops must remain unanswered." Thus China produces not only large amounts of rice but also wheat. The statistical data for China especially are fragmentary and unreliable. Rice is prepared for human consumption mostly by boiling rather than by milling and baking. Percival (18), however, comes out with a stronger statement than Zimmermann to the effect that "although rice is the principal food of a large proportion of the

human race, a greater amount of wheat is grown and this in the form of bread, constitutes the chief food of the most highly civilized races."

Wheat is grown primarily for direct human consumption. However, in areas removed from the central markets and also during periods of low prices, a considerable quantity of the crop may be used for feed. Thus the Pacific Northwest has always used a rather high percentage of its wheat crop for feed. As a matter of fact in portions of this area wheat produces more feed per acre than can be obtained from any other crop. Under ordinary conditions wheat is generally too valuable to be used for feed, except for special enterprises, and even then mostly wheat of low quality is used.

Historical. The cultivation and utilization of wheat is older than the written history of man. Its cultivation was general in western Asia at the dawn of history. Wheat was known to the Chinese in the twenty-eighth century B.C. The Chinese consider the crop native to their country, but evidence seems to indicate that wheat is native to the dry Mediterranean climates of Asia Minor and Mesopotamia.

Wheat is often spoken of as a frontier crop, and rightly so. In all countries suited to wheat production the wheat crop occupied, and in regions still occupies, an important place in financing the agricultural, transportational, and other improvements of frontier communities. This was the case in the United States. As agricultural production moved westward toward the drier plains area, wheat production advanced with it. In the course of time, as communities became more firmly established, the relative importance of the crop decreased in the eastern more humid areas in the shift from monoculture to more diversified farming.

Not without very important effects on wheat production and expansions of the world's wheat areas were the advances made in milling technology. Of special significance was the shift from the old-fashioned buhr stones to the steel roller milling process. This change in milling technique encouraged the production of the hard red spring and winter wheats now the outstanding crops of the grassland wheat producing areas of the world. Prior to the time of the introduction of the steel roller, or "gradual reduction," process the soft and semisoft wheats commonly produced in humid

areas were regarded as being more desirable for milling than the hard wheats.

CLIMATIC RELATIONSHIPS

General Climatic Areas. The general climatic relationships in the important wheat producing areas of the world are summarized in Table 20. It will be observed that wheat is grown under a great variety of climatic conditions. Percival points out that the cultivation of wheat is simple, and "its adaptability to varying soils and climatic conditions superior to that of any other plant." The most extensive wheat growing areas have continental, grassland climates, although wheat production is by no means limited to these climates. Köppen's and Thornthwaite's classifications bring out that the crop is grown primarily in areas with moderate temperatures and under subhumid and even semiarid conditions. Wheat is also grown under humid conditions as in northwestern Europe (Cfb and BC′r) and in the eastern portion of the United States (Dfa, Cfa, and BC′r). In India the crop is produced under high temperature conditions (Cwg and CA′w). Wheat in India is sown in October, after the cessation of the monsoon rains; that is, the crop is grown during the cooler and also drier portion of the year. The highest temperatures in the Indian wheat producing areas come prior to the occurrence of the monsoon rains. The wheat crop of China is also produced in territories with rather high temperatures, but under conditions of relatively low winter rainfall (Cw and BB′w). The wheat crop is out of the way before the hot humid weather of the summer months so favorable to rice growing arrives.

Köppen's and Thornthwaite's climatic formulas will be referred to from time to time in the discussions of climatic factors in this and succeeding chapters. It is often desirable to give the formulas of both classifications. In order to avoid confusion, Köppen's formula will always be given first, followed by Thornthwaite's. The two may of course be identified at any time by the fact that the temperature province of the Thornthwaite formula, the second capitalized letter, is always graced with a prime mark.

Bennett and Farnsworth (3) utilized Thornthwaite's classification of climates in discussing the climatic relationships in the wheat producing areas of the world. It is interesting to list here their estimates of the acreages in millions of acres for 14 of Thornthwaite's

TABLE 20. CLIMATIC RELATIONSHIPS IN THE IMPORTANT WHEAT PRODUCING AREAS OF THE WORLD

Producing Region	*Climatic Classification*			
	Relative Location	Vegetation	Köppen	Thornthwaite
U. S. southern Great Plains	Cont.	Grassland	Cfa	CB′r CB′d DB′d
U. S. northern Great Plains	Cont.	Grassland	Dfb BSkw	CC′d DC′d
Prairie provinces of Canada	Cont.	Grassland	BSkw Dfb	CC′d DC′d
Hungarian plains	Cont.	Grassland	Cfx Dfa	CC′r BC′r
Southern Russia	Cont.	Grassland	Dfc BSk	CC′r CB′d
Italy and Mediterranean .	Trans.*	Woodland	Csa Dfc	CB′s BB′r
France	Marine Trans.	Woodland	Cfb	BC′r
Argentina	Cont.	Grassland	Cfx′	CB′r
India	Cont.	Grassland	Cwg	CA′w
China	Cont.	Woodland Grassland	Cw Dwa	BB′w CB′w
Australia	Trans. Cont.	Grassland Woodland	BSks Csb	CB′s CB′d

* Transitional between marine and continental.

climatic types: CC′d, 58; DC′d, 46; CB′w, 40; CB′d, 34; DB′d, 28; BC′r, 25; CC′r, 25; BB′r, 21; CB′r, 21; CB′s, 20; CA′w, 16; BB′w, 13; DB′s, 11; and DB′w, 9. A tabulation such as this is misleading in bringing out the climatic relationships of wheat production unless it is considered in relation to the yields obtained in the various areas. The highest yields are obtained in the BC′r and CC′r climates. In these relatively moderate and moist climates wheat comes of course into more direct competition with other crops than in cooler and drier climates. Bennett and Farnsworth present an interesting and instructive map of world wheat yields. This map is of special value in discussing the limiting factors encountered in the various wheat producing areas of the world. It is evident from a tabulation of climatic types prevailing in the wheat producing

areas that production in many of these regions crowds the minimal areas.

Temperature Relationships. As already indicated, wheat is grown under a variety of temperature conditions. The prevalence of extremely low temperatures during the winter months, especially when there is no protective snow cover, necessitates a shift from winter to spring wheat. Wheat may be grown under rather high temperature conditions provided that the period of high temperatures does not coincide with periods of high atmospheric humidity. A combination of high temperature and high humidity is fatal to wheat. Thus as indicated by Baker (1) very little wheat is grown in the southeastern portion of the United States where the average temperature for the two months preceding harvest exceeds 68°F and where the rainfall amounts to 50 inches or more annually. These same factors are responsible for setting the northern limits of wheat production in Argentina, the eastern boundary of the wheat belt in India, and the expansion of wheat into southern China. In all of these territories the limits of production are set by the fact that a combination of high temperature and high humidity is encountered during the growing season of the wheat crop.

Winter wheat in order to survive demands specific temperature and moisture conditions during the autumn and winter months. These conditions were discussed in detail in Chapter XVI. Between 75 and 80 per cent of the world's wheat crop consists of winter wheat. In regions favoring survival higher and more stable yields can be generally expected from fall-sown than from spring-sown wheat.

Spring wheat requires a growing season of at least 100 days. Some wheat is being grown in areas with shorter growing seasons than that; production, however, is not extensive. The production of wheat in regions with short growing seasons is subject to a considerable frost hazard prior to maturity. In these same areas late spring frosts corresponding with the flowering and early stages of kernel development constitute a hazard in the production of winter wheat and also winter rye. In spite of these limitations, Baker states that only barley, potatoes, and certain hay crops are grown under colder conditions than wheat. According to Schindler (21) the northern limit of economical wheat production corresponds with the May isotherm of 10°C (50°F).

Moisture Relationships. The most important wheat producing areas of the world have an annual precipitation of less than 30 inches. Moisture conditions are analyzed to best advantage on the basis of efficiency of precipitation and humidity provinces, rather than from the standpoint of annual receipts of precipitation alone. In areas with a high efficiency of precipitation and with the crop grown under conditions of alternate fallow and cropping, wheat has been grown under as little as 10 inches of annual precipitation. It should be kept in mind, however, that the production of the crop becomes increasingly hazardous as the minimal moisture areas are approached. The seasonal distribution of precipitation as found in the grassland areas is ideal for wheat production, and especially for the growing of high-protein wheats. Since, however, these regions are characterized by a high variability in rainfall, the yields realized may be expected to fluctuate materially from season to season. As already indicated, high rainfall alone does not exclude wheat except where combined with high temperature. Such a combination favors the development of a host of fungus diseases.

Winter wheat demands for its best development favorable moisture conditions during the autumn months. This is essential to the proper establishment of the plants prior to the advent of the period of dormancy enforced by low temperatures during the winter months. Here is another weakness of the grassland climates. In occasional seasons a definite critical period is brought about by the absence of the expected autumn rains. In certain areas adapted to both spring and winter wheat the relative importance of these two types is greatly influenced by prevailing moisture conditions during the autumn months. Dry autumns unfavorable to the germination and establishment of winter wheat result in increased acreages of spring wheat and also of spring-sown barley.

Too many economists and geographers in discussions relating to the wheat producing potentialities of the world are prone to underestimate the physiological dependence of the wheat plant upon climatological factors, and upon moisture relationships in particular. While wheat is able to grow in relatively dry climates, the yields obtained in dry regions are not only low but also extremely variable. Many of the wheat producing areas of the world border on distinctly minimal moisture areas, and in places extend into them. Again, the possibilities of increasing yields are often

overstressed. In many areas, and especially in those favored with proper climatic conditions, increases in yields are possible. Nevertheless, in sections approaching the minimal areas it is necessary to recognize definite physiological limits. In many of these areas wheat yields have shown negative trends, even with the employment of improved varieties and methods of culture, after the level of fertility of the virgin soils pressed into wheat production has been reduced. The successive reductions of the organic matter content of such soils with continued cropping to wheat have a decided effect on water relationships.

SOIL RELATIONSHIPS

Fertility and Water Relationships. Wheat is grown under a wide range of soil conditions, yet the crop is quite specific in its soil requirements. The best wheat soils are fertile, have good water-holding capacities and fair to good drainage. Extremely sandy soils are not adapted to wheat production. Since wheat is being grown primarily in subhumid and even in semiarid sections, the soils are either neutral to slightly alkaline in reaction. The crop, while able to withstand a moderate concentration of soluble salts and even carbonates, is not adapted to strongly saline or alkaline conditions. Production in humid areas takes place largely on soils that are slightly acid.

The Chernozem and Chestnut soils are especially important in wheat production. Production is less hazardous on the Chernozem than on the Chestnut soils because the former are found in areas with higher P–E indices than the latter. Wheat production on the Grayerths is possible in most areas only with the aid of irrigation.

Good wheat soils contain fairly large amounts of available phosphorus. This promotes the formation of grain. A favorable organic matter content of the soil is desirable to promote good tilth. A moderate liberation of nitrogen is desirable, not only for the stimulation of growth, but also for the production of high quality, high-protein wheats.

THE DISTRIBUTION OF WHEAT

World Centers of Production. Figure 67 shows the wheat producing areas of the world. Twelve more or less distinct wheat producing areas stand out prominently:

1. The northern Great Plains area of North America.
2. The southern Great Plains area of the United States.
3. The Columbia River basin and Palouse area of the United States.
4. Northwestern Europe.
5. The Mediterranean area of Europe and northern Africa.
6. The Hungarian plains.
7. The Danube basin.
8. Southern Russia.
9. Northwestern India.
10. East-central China.
11. Argentina.
12. Southeastern Australia.

Table 21 gives the statistical data of important wheat producing countries.

The three outstanding wheat producing areas of the North American continent are in grassland regions. The southern Great Plains area produces winter wheat. The northern Great Plains of the United States extending into the prairie provinces of Canada represents the largest contiguous highly specialized spring wheat producing area of the world. The Pacific Northwest produces both winter and spring wheat.

The United States is still an important exporting country; exports have, however, been decreasing. This is partly due to increasing population and greater home consumption, but also to a high degree to complications in international trade since the depression. The fact that the United States changed its status from a debtor to a creditor country with and after the first World War materially influenced its position as an exporter of wheat. Canada's position as an export country remains supreme. The average exports from Canada for the period 1930–1934 amounted to around 224 millions of bushels as compared to only slightly over 59 millions of bushels for the United States. Canada is a great producer and on account of its relatively small population and economic status a great exporter of wheat. Canada is recognized as the outstanding producer of exceptionally high quality spring wheat.

Northwestern Europe is not only highly industrialized, but has also a highly specialized and productive agriculture. This is evident

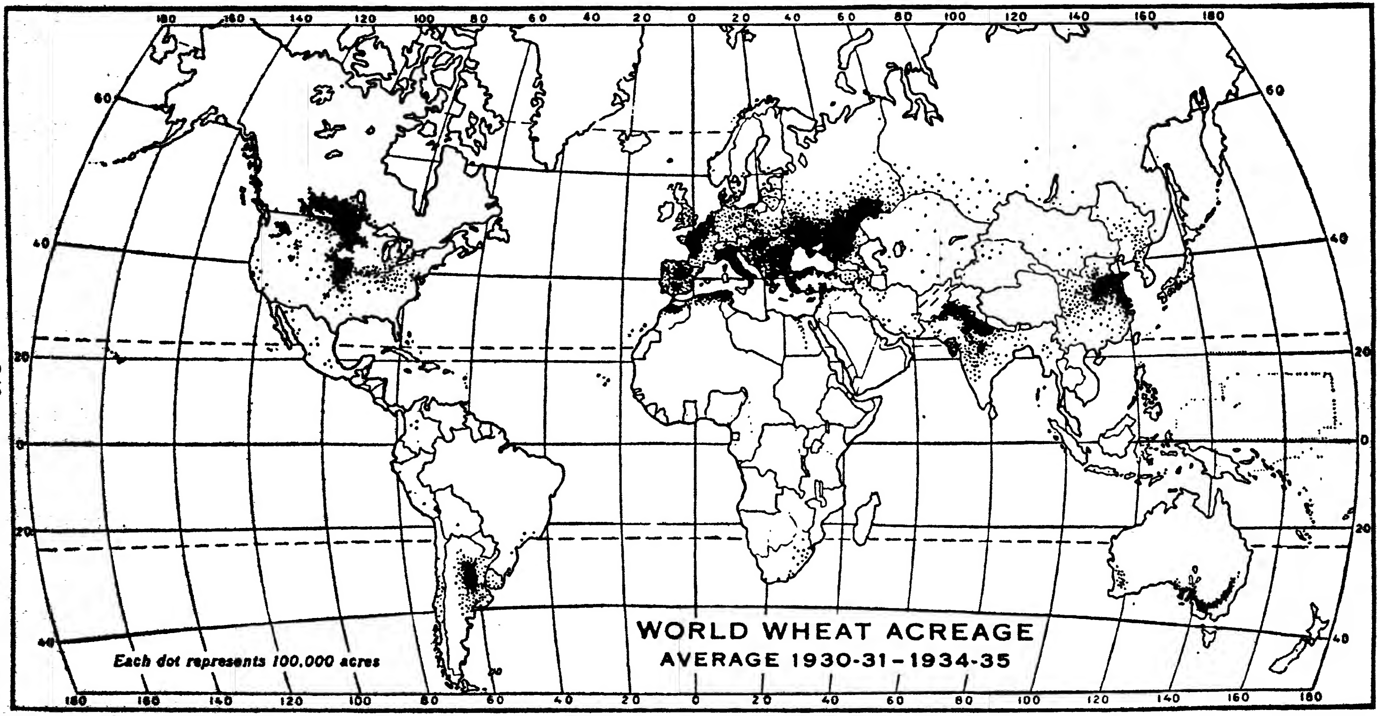


FIG. 67. World wheat production. Each dot represents 100,000 acres (U. S. Dept. of Agr. Bur. of Agr. Econ.)

TABLE 21. WHEAT: ACREAGE, YIELD PER ACRE, PRODUCTION, AND PER CENT OF WORLD TOTAL PRODUCTION IN SPECIFIED COUNTRIES — AVERAGES FOR THE FIVE-YEAR PERIOD 1930–31 TO 1934–35

Rank	Countries	Acreage, in Millions of Acres	Yield, in Bu. per Acre	Production	
				In Millions of Bu.	In Percentage of World Total
1	U.S.S.R., European and Asiatic	85.80	10.8	924.54	16.81
2	China	—	—	778	14.14
3	United States	54.19	13.5	732.63	13.32
4	India	33.34	10.7	355.59	6.47
5	Canada	25.68	13.6	348.56	6.34
6	France	13.28	23.0	305.32	5.55
7	Italy	12.17	20.8	252.60	4.59
8	Argentina	17.71	13.8	243.93	4.44
9	Germany	7.97	29.7	236.54	4.30
10	Australia and New Zealand	15.49	12.5	193.81	3.52
11	Spain	11.24	14.1	158.08	2.87
12	Northern Africa	10.33	11.4	118.16	2.15
13	Rumania	7.70	13.4	103.45	1.88
14	Yugoslavia	5.10	15.6	79.49	1.45
15	Hungary	3.94	19.4	76.51	1.39
16	Poland	4.26	17.4	74.27	1.35
17	Great Britain	1.56	33.9	52.87	0.96
18	Bulgaria	3.08	17.2	52.86	0.96
	All others	—	—	412.79	7.51
	World total production	—	—	5,500.00	100.00

from the acreage and especially from the yield data presented in Table 21. Climatic conditions in this area are generally favorable to wheat production. In many areas soil conditions, however, do not favor the crop. In such areas, either soil conditions are ameliorated through the application of scientific principles, crop rotations, and fertilizations, or, if the soils are sandy, the wheat crop yields its place to rye. The substitution of rye for wheat holds true especially on the expanses of sandy and peat soils along the North and Baltic Seas. Wheat production is highly developed in northern and central France, western England, and on the heavier soils of central Germany. The recent trend toward national self-sufficiency has given a great impetus to the expansion of wheat acreage and production in central Europe and in Italy.

As stated by Whitbeck and Finch (27), "the agricultural lands of Europe are the continent's greatest resource, and the quantity of

foodstuffs produced is greater than in North and South America combined." One of the richest and most dependable of the wheat producing areas of the continent are the Hungarian plains. Here is found a happy combination of favorable climatic and soil conditions for wheat production, making it a virtual granary for central Europe. An even more extensive though not so reliable wheat producing area is found across the Transylvanian Alps, that is, in the Danube basin extending through Walachia, Dobruja, Moldavia, and Bessarabia. In this area, soil conditions favor wheat; climatic conditions are, however, more hazardous than on the Hungarian plains. Droughts during the growing season occasionally reduce yields on the Hungarian plains; they are, however, not so common there as in the Danube basin.

Southern Russia is a wheat producing empire. The heaviest distribution of wheat in Russia corresponds with the extension of the Chernozem. The Ukrainian and Crimean areas are of special importance. The Russian wheat producing areas are with respect to prevailing soil and climatic conditions quite similar to those of the Great Plains area of North America. The southern portion of the Russian wheat belt produces winter, the northern interior, spring, and the driest interior areas a rather high percentage of durum wheat. Climatic conditions are extreme. The size of the crop in any given season is highly dependent on moisture and temperature conditions, that is, the crop is produced under grassland and steppe climates and shows the high degree of variability common to such areas. It should be mentioned that many of the hardy varieties of wheat and oats produced in the United States originated in the cereal producing area of Russia with its extremes of dryness, winter cold, and summer heat. Prior to the first World War, Russia was the world's most important exporter of wheat. Since that time, Russian wheat exports have been held within moderate limits. Russia, while the greatest wheat producing country of the world, has a large and growing population. Furthermore, indications are that the standards of living of the masses of the people have improved since prewar days and will probably continue to improve. Consequently the prospects of Russia's ability to regain her former preeminence as an exporter of wheat seems rather remote (Timoshenko, 25, 26, and Strong, 24).

The climates of Asiatic Russia are generally too dry and cold

for intensive wheat production. This is evident from the climatic maps presented in Chapter XX. Marbut (16) overestimated the wheat producing potentialities of Russia and especially of Siberia. This statement is borne out by Zimmermann. "The expansion of agriculture in European Russia is almost impossible, and the potentialities in Siberia and central Asia are far less than is generally believed." Also Timoshenko (26) states that

> "further expansion of the agricultural area in Asiatic Russia on new unoccupied lands must go rather slowly, for it will generally require reclamation and improvement of land (drainage of marshy land in taiga regions and irrigation on the dry steppes). Comparatively rapid expansion of the crop area here may proceed for some time only in the area having from 10 to 14 inches of rainfall annually, where hazardous dry farming must be practiced. Even expansion of the area devoted to this hazardous dry farming will require considerable development of the railroad system in Asiatic Russia."

Wheat is an important crop on all the arable lands bordering the Mediterranean. The Mediterranean climates (Csa, CB's) with their mild winters and warm bright summers are favorable to winter wheat production. Durum wheat is also a common crop, especially in northern Africa, Morocco, and Algeria.

Wheat production is an important enterprise in central and especially in northwestern India, that is, in the upper Ganges region and the Punjab. Much of the crop is grown under irrigation. As stated by Bergsmark (4),

> "Irrigation works in the Punjab have resulted in the opening to cultivation of large areas of relatively unleached, fertile soils which had hitherto been unsuitable for agricultural development because of lack of water. Such irrigation projects have resulted in the development of what is known as canal colonies. The results may be gauged from the fact that Lyallpur, the capital of the upper Chenab colony, now has a large export trade, and the population of which it is the center increased from 8,000 to 979,000 in the course of 15 years (1915–1930)."

The size of the wheat crop of India in spite of extensive irrigation developments is highly dependent on the timely arrival of the monsoon rains. If these rains come too late the crop will not mature before the arrival of high temperatures. Earliness is a common characteristic of Indian cereals. Durum and also club varieties are grown in the drier districts. India is now of only minor impor-

tance as an export country. Its teeming population could, economic conditions permitting, consume more wheat than is produced even in favorable seasons. In former years the country exported great quantities of wheat in favorable seasons. Production, however, was not dependable. In some years no exportable surplus was produced, whereas in others it exceeded 80 millions of bushels. Such fluctuations attest the variations in precipitation.

Statistical data on wheat production in China are fragmentary. The figure of total production given in Table 21 is at best a rough estimate. The crop is of special importance in the east-central portion of the country. There is, however, a considerable overlapping with the main rice producing areas farther south. Wheat occupies the land during the portion of the year too cool for the growing of rice.

The reason for the limits of wheat expansion in northern Argentina has already been indicated. In the remainder of Argentina possible expansion is limited by lack of rainfall. The country becomes increasingly dry as the interior is approached. The climate especially in the interior regions is typically grassland, and the crop is subject to the uncertainties of such climates. Owing to the small population and low aggregate consumption, Argentina occupies a prominent place as an export country, being second only to Canada as an exporter of wheat. The average annual export for the period 1930–1934 amounted to 134 million bushels. It is followed closely by Australia, with more than 124 million bushels per annum for the same period. The fact that the Argentine wheat crop is grown in close proximity to navigable waters favors export trade. Southeastern Australia is favored by the same condition but has the obstacle of greater distance to European markets. Wheat is the most important crop of Argentina from the standpoint of acreage, followed by corn, alfalfa, and flax.

Limited rainfall causes the acreage suited to wheat production in Australia to be relatively small. However, southeastern Australia leads all other territories of the world in the proportion of cultivated land in wheat. Earliness is a general characteristic of the varieties used. As southwestern Australia is very dry, production there is small. Some durum wheats and early-maturing varieties of common wheat are being grown. Because of a small population, a high percentage of the crop is available for export.

Distribution of Wheat in the United States. The distribution of wheat in the United States emphasizes the importance of the grasslands in wheat production. Thus, according to Baker and Genung (2), 70 per cent of the wheat acreage of the country was in the Great Plains states in 1929. This is evident from Fig. 68. Wheat production is, however, not limited to the grassland areas. It is an important cash crop entering into the rotations common to the eastern Corn Belt, and in the limestone valleys and Piedmont from Pennsylvania to North Carolina.

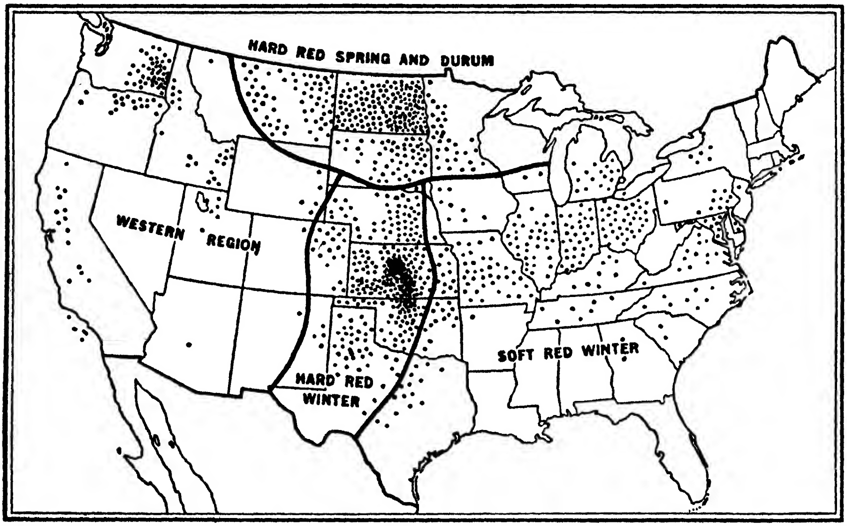


Fig. 68. Distribution of wheat and the classes of wheat produced in the different areas of the United States, average acreage harvested 1928–1937. Each dot represents 50,000 acres.

Table 22 gives the statistics of wheat production by important producing states. The states of the Great Plains area are much in evidence; other states with acreages in grassland climates with a winter concentration of rainfall are Washington, Idaho, and Oregon.

Figure 68 shows not only the distribution of wheat in the United States but also the classes of wheat produced in the different areas. The soft red winter wheats in the eastern portion of the country are accounted for by the high humidity generally encountered there. In low-moisture years a considerable percentage of the wheat produced in Illinois and Indiana will grade hard. The line

of demarcation between the spring and winter wheat producing areas is fairly distinct. There is, however, some overlapping in South Dakota, Nebraska, and Minnesota. Durum wheat production is concentrated in northeastern South Dakota and the eastern half of North Dakota. The western region grows several types of wheat, hard red winter, white, and club. Both winter and spring wheats are grown in the western region. Most of the irrigated sections specialize on spring wheat, while winter wheats predominate in the dry land areas.

TABLE 22. WHEAT: ACREAGE HARVESTED, PRODUCTION, AND PERCENTAGE OF UNITED STATES TOTAL PRODUCTION IN SPECIFIED STATES RANKED ACCORDING TO PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGES AND PRODUCTION EXPRESSED IN MILLIONS OF ACRES AND BUSHELS.

Rank	*States*	*Acreage Harvested*	*Production*		
			Average 1928–1937, in Bu.	Percentage of U. S. Total, 1928–1937	1938, Bu.
1	Kansas	10.68	138.07	18.34	152.18
2	North Dakota	8.02	73.74	9.79	76.38
3	Oklahoma	3.95	47.05	6.25	61.68
4	Nebraska	3.18	46.25	6.14	55.71
5	Washington	2.21	43.73	5.81	54.59
6	Ohio	1.85	36.57	4.86	46.42
7	Montana	3.35	35.22	4.68	69.52
8	Illinois	2.01	34.53	4.59	41.79
9	Texas	3.00	32.04	4.26	35.05
10	Indiana	1.66	28.45	3.78	28.85
	All others	15.89	237.30	31.50	309.53
	Total U. S.	55.80	752.95	100.00	931.70

RYE

Commercial Importance. Rye is the world's second most important bread crop. While rye still holds an important place as a bread crop in Russia, Germany, and the Scandinavian countries, the long-time tendency has been to make more and more use of it as a feed crop. Shollenberger (22) for instance makes the observation that "in some European countries which formerly were predominantly rye-bread-consuming rye has already come to be con-

sidered a feed grain. The British Isles offer a notable example of this; a few centuries ago rye was the principal bread grain but today annual consumption amounts to less than two pounds per person. For more recent indications of this tendency Norway and Sweden offer the best examples." Improvement in means of transportation and the expansion of world trade no doubt played an important part in this trend away from rye to greater wheat consumption. Depressions, stagnations of trade, and national emergencies will tend to retard this movement toward the greater utilization of wheat. Rye consumption remains high in Germany and the Scandinavian countries, as well as in all the other countries bordering the Baltic. In some of these countries economic conditions must improve materially before a great decline in rye consumption may be expected.

In the United States the consumption of rye bread has never been of importance; rye bread is considered as a novelty rather than as a staple food product. Even when rye is used for bread it is in most instances mixed with wheat. Rye is used extensively in the production of distilled spirits and alcohol. The quantity used for this purpose for the fiscal year ending June 30, 1937, amounted to over 11½ million bushels.

Rye has other notable uses than as a bread and grain feed, namely as a pasture, soiling, cover, and green manure crop. The long straw of rye is also highly prized.

Historical. Hughes and Henson (11) note that "compared to wheat, rye is a relatively new crop. It is not mentioned in old Chinese and Japanese literature and DeCandolle states that it has not been found in Egyptian monuments. The earliest cultivation of rye appears to have been in western Asia and southern Russia." According to Engelbrecht's conception, cited by Schindler, cultivated rye, *Secale cereale*, originated from *S. anatolicum* reported as a weed admixture in wheat fields of Asia Minor. The wheat with its admixture of rye is reported to have been carried by the ancient Greeks to southwestern Russia, where the "weed" was elevated to the position of a cultivated crop. From there it was carried to the north and northwest where it was destined to become the most important bread crop of the Germanic and Slavic peoples.

Climatic Relationships. Rye has the distinction of being the most winter-hardy of the cereals. Only spring-sown barley is

grown farther north and at higher elevations than winter rye (Carleton, 6). Both winter and spring varieties of rye are available; most of the crop is, however, fall-sown.

Table 23, listing the essential features of the climates of the world's important rye producing areas, brings out that rye is a cool-weather crop. Its distribution extends from the mild Cf to the boreal Df climates. It is not found in warm climates except in instances as a winter cover crop. According to Schindler, the northern limit of rye production in Europe corresponds fairly well with the July isotherm of 18°C (65°F). Its expansion to the south extends to the May isotherm of 15°C (59°F) or the July isotherm of 20°C (68°F). South of this line wheat takes its place.

Rye is grown over a wide range of moisture conditions. The Cfb, Dfb to BSk, and CC′r to CC′d climates are represented in the producing areas. The fact that the crop matures early enables it to escape drought.

TABLE 23. CLIMATIC RELATIONSHIPS IN THE IMPORTANT RYE PRODUCING AREAS OF THE WORLD

Producing Region	*Climatic Classification*			
	Relative Location	Vegetation	Köppen	Thornthwaite
Russia	Cont.	Grassland Woodland	Dfb BSk	CC′r CC′d
Germany and Poland	Trans. Cont.	Woodland	Cfb	CC′r
U. S. northern Great Plains . . .	Cont.	Grassland	Dfb	CC′r CC′d

Soil Conditions. Rye is found and extensively grown as a bread crop not only in cold and bleak climates but also on poor, sandy soil. No other cereal can be grown and be depended upon to supply the "daily bread" under such severe conditions. It is no small wonder that Thaer designated the crop as the "most benevolent gift of God."

The soil relationships of rye are well stated by Morgan *et al.* (17) in the following paragraph.

"Rye is less exacting in its soil requirements than any of the other important cereals. It grows well over a wide range of conditions with

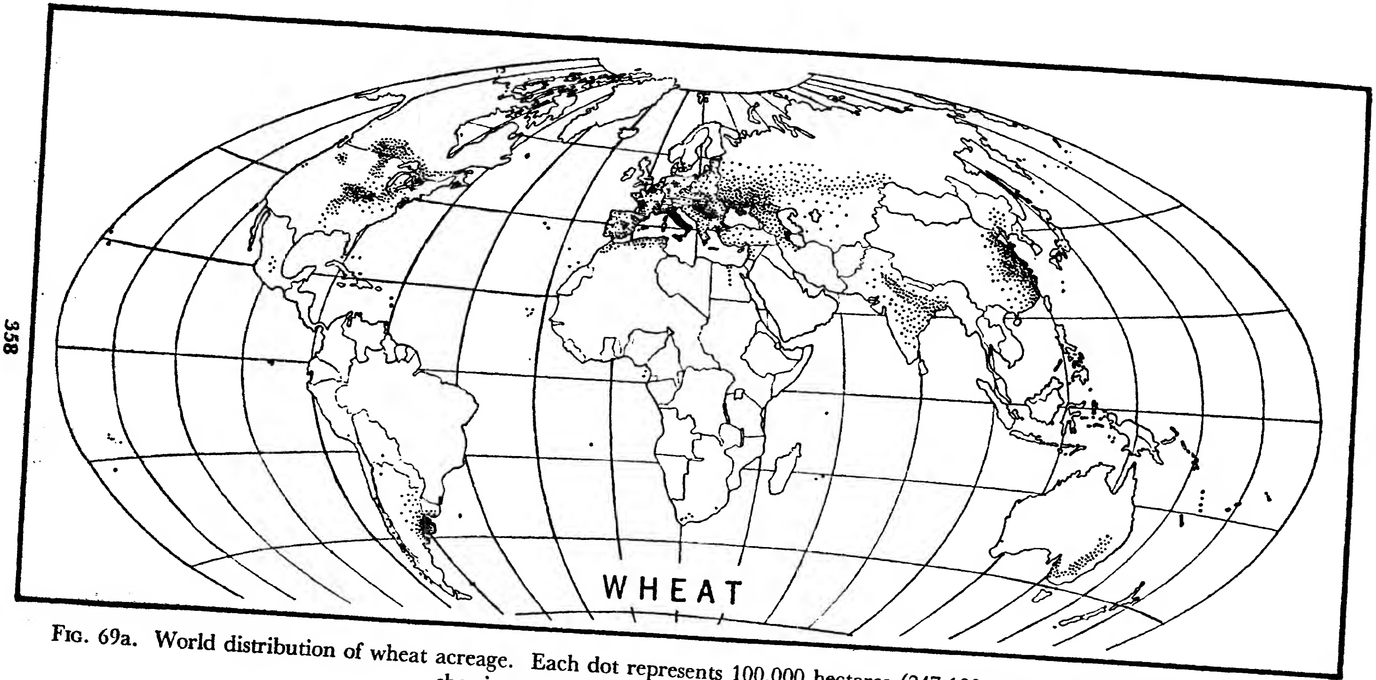


FIG. 69a. World distribution of wheat acreage. Each dot represents 100,000 hectares (247,100 acres). Compare with Fig. 69b, showing world rye distribution. (After Kirsche.)

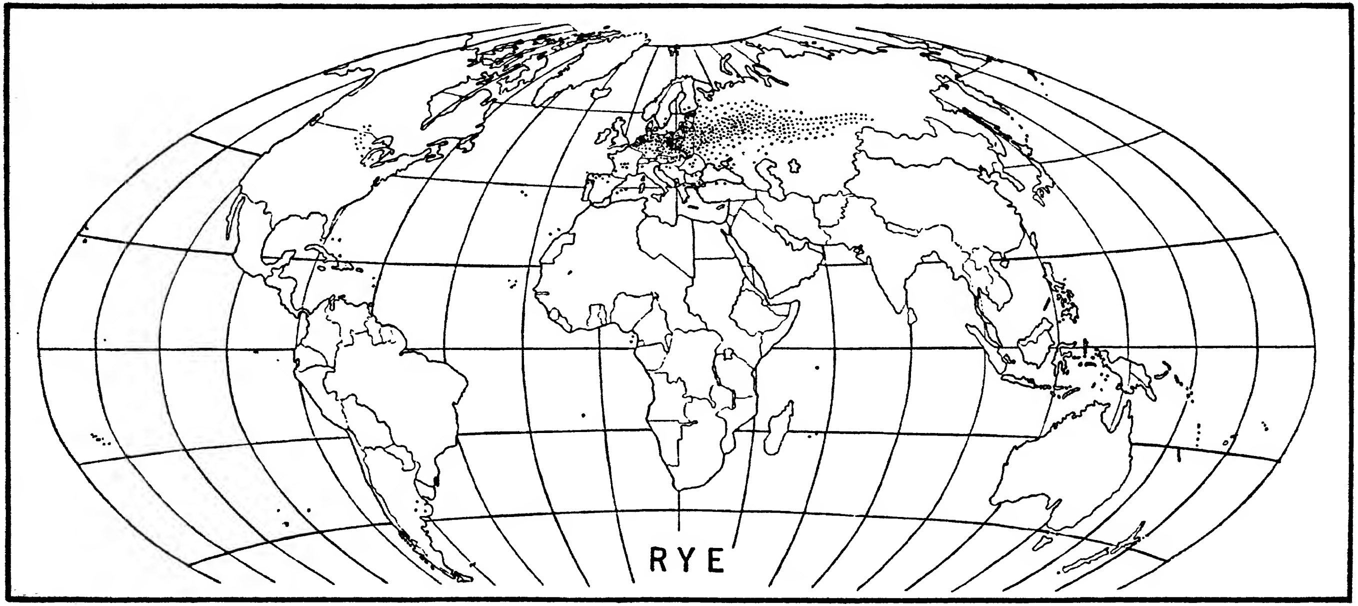


Fig. 69b. World distribution of rye acreage. Each dot represents 100,000 hectares. Compare with Fig. 69a, showing world wheat distribution. (After Kirsche.)

respect to soil moisture, although it is adversely affected by deficient drainage. It is able to withstand considerable degrees of acidity and alkalinity. The crop makes a reasonable growth at low levels of fertility, both with respect to available nitrogen and mineral nutrients. On the other hand, it is able to make a relatively luxuriant growth under especially favorable conditions without damage to grain quality. Losses due to lodging from excessive nitrates are much less than with wheat and oats."

World Distribution of Rye. Rye is essentially a European crop. That continent accounts for around 96 per cent of the world's total production.

Table 24 gives the statistical data on world rye production, while Figures 69a and 69b, compiled from Kirsche (14), compare the world distribution of wheat and rye. The rye producing area of Europe extends across the continent as a continuous belt from northern France into Siberia. The wheat and rye producing areas are somewhat complementary; in general, however, rye occupies a more

TABLE 24. RYE: ACREAGE, YIELD PER ACRE, PRODUCTION, AND PERCENTAGE OF WORLD TOTAL PRODUCTION IN SPECIFIED COUNTRIES — AVERAGES FOR THE FIVE-YEAR PERIOD 1930–31 TO 1934–35

Rank	*Country*	*Acreage, in Millions of Acres*	*Yield, in Bu. per Acre*	*Production*	
				In Millions of Bu.	In Percentage of World Total
1	U.S.S.R.	65.29	13.5	881.29	47.60
2	Germany	14.61	27.4	400.76	21.65
3	Poland	14.20	17.9	254.38	13.74
4	France	1.75	18.3	32.02	1.73
5	United States	2.92	10.7	31.27	1.69
6	Hungary	1.58	18.0	28.48	1.54
7	Lithuania	1.23	18.4	22.62	1.22
8	Spain	1.49	14.8	22.16	1.20
9	Belgium	.52	38.6	20.07	1.08
10	Sweden	.56	30.2	16.79	0.91
11	Netherlands	.44	35.6	15.66	0.85
12	Finland	.55	24.9	13.77	0.74
13	Rumania	.94	14.6	13.73	0.74
14	Latvia	.63	19.8	12.40	0.67
15	Argentina	.94	10.5	9.87	0.53
16	Canada	.86	10.4	8.94	0.48
	All others	3.78	17.7	67.08	3.63
	World total	112.29	16.5	1,851.29	100.00

northerly position than wheat. This is accounted for by soil and climatic factors.

The reader should not draw the conclusion that rye is grown only in poor soils. This is not the case. In general, the extensive acreages occupied by the crop in central Russia and also in the northern Great Plains area of the United States are found on good soils. On the other hand, rye is the main cereal crop on the great expanses of sandy and heath soils of northern Germany and the Baltic countries. In some of these areas crop production would be virtually impossible except for the remarkable characteristics of the rye plant. It is interesting to note that the yields in the western European countries are high in spite of the fact that the crop is widely grown on poor soils.

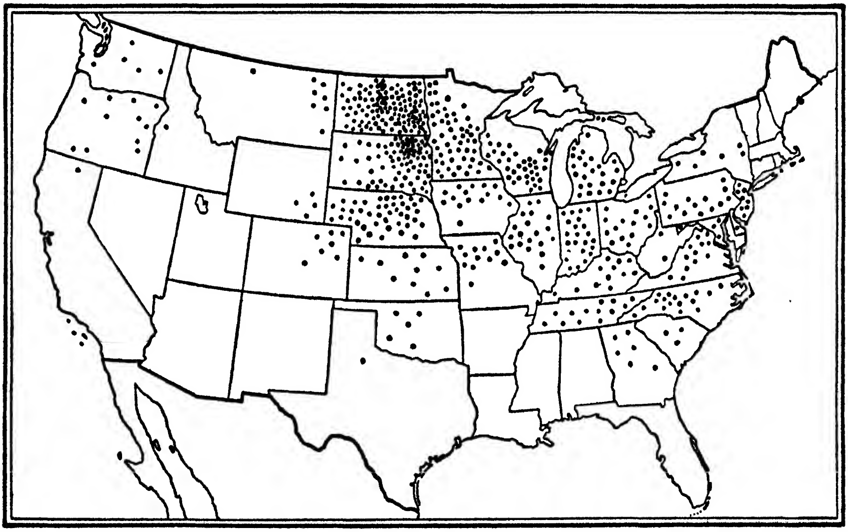


Fig. 70. Distribution of rye in the United States, average acreage harvested 1928–1937. Each dot represents 10,000 acres.

Distribution of Rye in the United States. Prior to the first World War rye was grown principally in the sandy sections of Michigan, Wisconsin, and Minnesota, with a smaller acreage on poor and depleted soils in Pennsylvania, New Jersey, and eastern New York. Since that time the states of the northern Great Plains area have assumed the lead. This is shown in Table 25 and Fig. 70. Since wheat production is excluded by severe winter conditions of the northern Great Plains, rye fills the distinct need for a fall-

sown crop. Its inclusion in the cropping systems of this area lends stability and diversification. Winter rye can often be relied upon to provide feed in seasons disastrous to spring wheat and other spring-sown crops. In recent years the importance of rye has also increased in the central and southern Great Plains area. This increase may be accounted for by the response of rye to droughts experienced in this area. Owing to dangers of admixtures, winter rye should under most conditions be excluded from intense winter wheat producing areas.

TABLE 25. RYE: ACREAGE HARVESTED, PRODUCTION, AND PERCENTAGE OF UNITED STATES TOTAL PRODUCTION IN SPECIFIED STATES RANKED ACCORDING TO PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGES AND PRODUCTION EXPRESSED IN THOUSANDS.

Rank	*States*	*Acreage Harvested*	*Production*		
			Average 1928–1937, in Bu.	Percentage of U. S. Total, 1928–1937	1938, in Bu.
1	North Dakota	812	8,076	22.23	12,974
2	Minnesota	406	6,138	16.90	9,846
3	South Dakota	310	3,714	10.22	10,176
4	Nebraska	289	2,770	7.62	4,796
5	Wisconsin	228	2,515	6.92	4,290
6	Michigan	159	1,886	5.19	1,552
7	Pennsylvania	113	1,544	4.25	884
8	Indiana	118	1,370	3.77	1,265
9	Iowa	71	1,124	3.09	1,860
10	Illinois	80	971	2.67	1,350
	All others	593	6,222	17.14	6,571
	Total U. S.	3,179	36,330	100.00	55,564

BARLEY

Commercial Importance. Barley is primarily a feed crop. Its second most important use is in the production of malt. The amount used for that purpose is small in relation to the total crop produced. In the United States, the greatest beer producing country of the world, the amount of barley used in the making of fermented malt liquors for the fiscal year ending June 30, 1937, was 54.63 million bushels. In addition to this amount, 8.99 million bushels were used in the production of distilled spirits. Barley

occupies a rather minor place as a cereal for direct human consumption except in some northern areas of Europe and in Asia, and at high elevations; that is, under conditions too severe for the production of either winter wheat or winter rye. It is a staple food in the highlands of Tibet. In most areas it is used for human food only in special forms as in breakfast foods and as pearled barley in soups. Only around 1.5 million bushels of barley are used for pearling in the United States annually.

Barley is generally used in place of corn for feeding purposes in areas not adapted to corn production. Likewise barley takes the place of oats for feed in areas unsuited for oat production; as in northern Africa where the physiological growing season is cut short by hot dry weather in early summer.

Historical. Barley is one of the most ancient of cultivated plants. Körnicke agrees with Plinius in designating it as the oldest of cultivated plants. In ancient Egypt it was used as food for man and beast, and also made into bread. It continued to be one of the chief bread plants of continental Europe down to the sixteenth century, when it was gradually replaced by rye and wheat.

According to Carleton, *Hordeum spontaneum* is generally conceded to be the oldest ancestor of two-rowed barley now known to be growing wild. It occurs in all of the region between the Red Sea and Caucasus Mountains. Six-rowed barley originated, according to Körnicke, from a wild barley *H. ithaburense* found by Bornmüller in the Kurdistan Mountains of western Asia.

Climatic Relationships. Wheat has the distinction of being the prime bread crop of the world, rye the distinction of being the most winter-hardy of the cereals, while barley is outstanding from the standpoint of being able to mature in a shorter season than any other cereal crop. The season here referred to is the physiological growing season; that is, the growing season may be cut short either by the lack of a sufficient amount of moisture to sustain growth, or in northern areas and at high altitudes by low temperatures. The fact that barley is able to mature in a short season has won for it the reputation of being drought-resistant. This is not exactly the case; the crop is drought-escaping rather than drought-resistant. During its short period of growth it demands rather moderate temperatures and a fairly abundant supply of moisture. The intermountain states offer a good example of the ability of barley to grow at high

elevations. Robertson *et al.* (19) report high yields of barley at the Fort Lewis substation in Colorado at 7,000 feet elevation, with a growing season of only from 90 to 100 days. Woodward and Tingey (28) also report good returns from barley at 7,000 feet in Utah. In eastern Idaho the crop is grown at 6,500 feet. In the Alps barley is found up to 5,500, in the Caucasus up to 8,500, and in Tibet even at 10,000 feet above sea level. The northern limit of barley in Russia is reported at latitude 65°.

Barley is able to grow under conditions of low temperature during its period of vegetative growth. It is also able to endure high temperatures during and after heading, provided the humidity of the air is low. A combination of high temperature and high humidity is as fatal to barley as to wheat. Such a combination is especially detrimental if occurring during the postheading period.

It is necessary to differentiate between the climatic requirements of feed and malting barley. One of the main prerequisites of a malting barley is mellowness, occasioned by a high starch content, capability of yielding a high percentage of extract, and a relatively low nitrogen content. The production of this type of barley requires above all temperature and moisture conditions favorable to the elongation of the postheading period. Hot dry weather after heading leads to the production of a harsh, flinty type of kernel unsuited for malting. A flinty type of grain relatively high in nitrogen can be used to good advantage in the feeding of livestock. Consequently areas bordering on sections where the growing season is cut short by hot dry weather usually produce a feed type of barley.

Table 26 gives the climatic relationships in the important barley producing areas of the world. The general climatic requirements of barley, it will be seen, are quite similar to those of wheat. As a matter of fact, the wheat and barley producing areas in North America and Europe show a considerable overlapping in most sections. There are exceptions to this, however; for instance the central portion of the Corn Belt and the southern Great Plains area grow but little barley; likewise, Italy has little barley. Both of these regions are important wheat producing areas. Several factors may be responsible for these exceptions such as the need for a bread crop, the competitive position of barley as a feed crop compared with other available grain feeds such as corn and the sorghums in the central and southern Great Plains area, and above all the fact that

the production of winter barley is more hazardous than that of winter wheat. Winter barley is grown only in areas with comparatively mild winters. It was pointed out in connection with the climatic requirements of wheat that the highest yields were obtained in the BC′r and CC′r climates. This holds true also with barley. There is a noticeable difference between the climatic responses of wheat and barley. The highest quality wheats, the high-protein or strong wheats, are produced in the relatively dry BSk and CC′d climates while the low-protein wheats are produced in the moister Cf and CC′r climates. The usually more valuable malting type of barley is produced in the moister, and the feeding and generally less valuable types in the drier, climates. The protein relationships in response to climatic factors are the same in wheat and barley; the difference comes into play in the designation of the standards of quality.

TABLE 26. CLIMATIC RELATIONSHIPS IN THE IMPORTANT BARLEY PRODUCING SECTIONS OF THE WORLD

Producing Region	*Climatic Classification*			
	Relative Location	Vegetation	Köppen	Thornthwaite
U. S. northern Great Plains	Cont.	Grassland	Dfb BSkw	CC′d CC′r DC′d
Wisconsin and northern Illinois	Trans.*	Woodland	Dfb Dba	BC′r CC′r
California	Trans.	Grassland Woodland	Cfb Csb	CB′s DB′d
Germany	Trans.	Woodland	Cfb Dfb	BC′r CC′r
Southern Russia	Cont.	Grassland	Dfc BSk	CB′d CC′r
Northern Africa	Trans.	Woodland Grassland	Csa BShs	CB′s DB′s
Northern India	Cont.	Grassland	Cwg	CB′w CA′w

* Transitional between marine and continental.

Soil Conditions for Barley. Barley is very specific in its soil requirements. It demands better drainage than either wheat or oats. For this reason it is not well adapted to heavy clay soils in humid areas. It is also more sensitive to mineral deficiencies than

wheat and less tolerant of soil acidity than most other cereals. On the other hand, barley withstands moderate concentrations of alkali and soluble salts. Sandy soils are unsuited to barley production.

World Distribution of Barley. Six more or less distinct world centers of barley production may be recognized from Fig. 71, giving the distribution of world barley acreage, and Table 27, showing the statistical data of barley distribution. These areas are:

1. The north central portion of the United States and the eastern parts of the prairie provinces of Canada.
2. Northwestern and central Europe.
3. Northern Africa and Spain.
4. Rumania and southern Russia.
5. North-central India.
6. Northeastern China and Japan.

The distribution of barley on the North American continent will be discussed under a separate heading.

Barley is an important crop on nearly all the better soils of northwestern and central Europe. Climatic conditions favor the production of malting barley. The crop is of special importance in Denmark, particularly on the island of Zealand. The great importance of the livestock industry in Denmark and northwestern Europe in general accounts for the great importance of barley; furthermore, the cool climate favors high yields. Barley is used extensively for feed in all of this area but is of less importance for that purpose than oats. There is a close agreement with the barley and sugar beet producing areas, barley being one of the crops most frequently following sugar beets in the rotation. Both of these crops require good soils.

The barley producing area of Europe extends across the entire continent from the North and Baltic Seas to the Black Sea. The crop becomes of special importance on the Chernozem soils of Rumania and in southern Russia. The climate in this area is rather dry, but barley is usually able to mature prior to the appearance of the expected summer drought.

Barley fits well into the Mediterranean climates of northern Africa and southern Spain. It constitutes the great feed crop of this area. The climate is sufficiently mild for winter barley which matures before the summer drought. The low humidity during

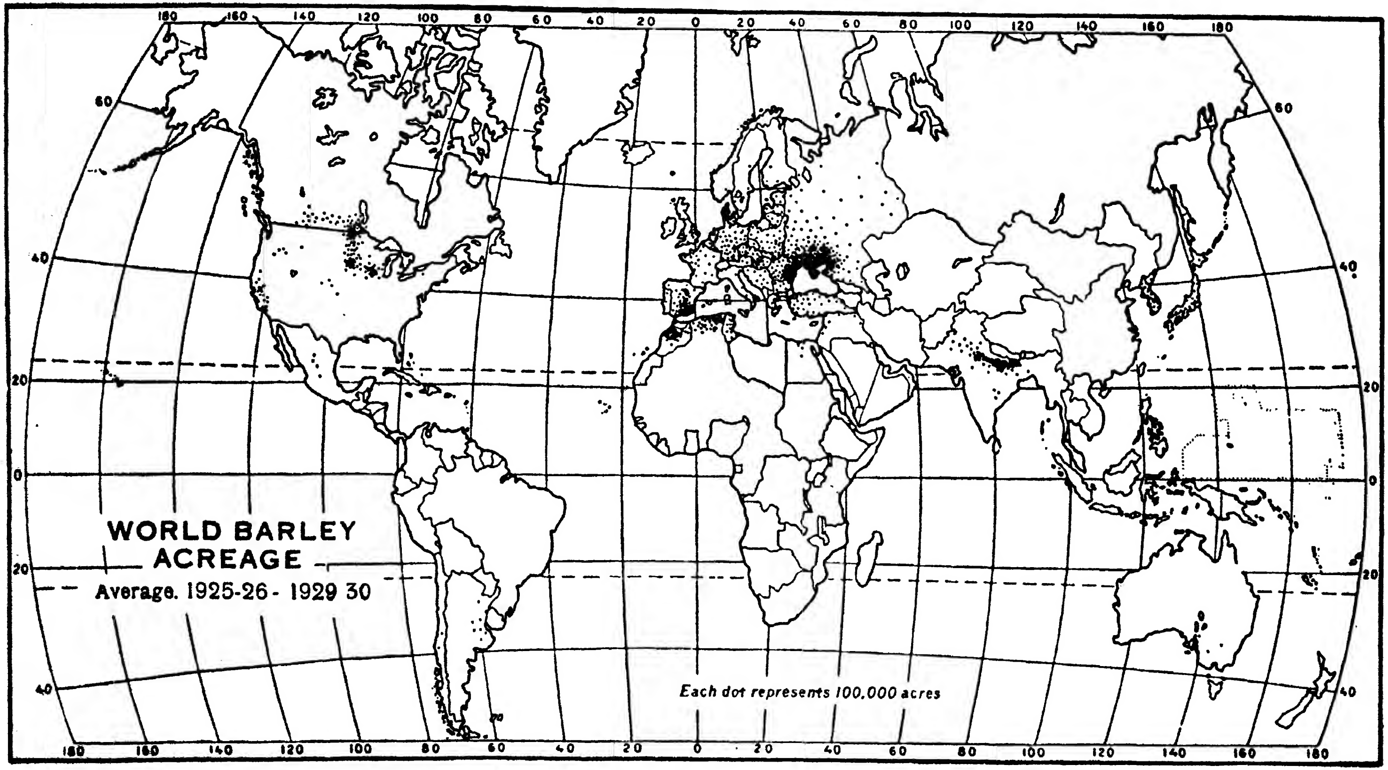


FIG. 71. World barley production. Each dot represents 100,000 acres. (U. S. Dept. of Agr. Bur. of Agr. Econ.)

the season when the crop approaches maturity enables it to withstand fairly high temperatures.

China and Japan are important barley producing countries. A considerable portion of the crop produced is used for human consumption. The producing areas correspond with the wheat growing sections, the crop filling the same place in the rotation as wheat in that it is grown during the portion of the year too cool for the production of rice. The hot, humid summers in this area are unfavorable to barley production. The barley crop, like fall-sown wheat, is able to escape this unfavorable season by virtue of its ability to grow at relatively low temperatures during late winter and early spring so that it matures before the hot, humid weather sets in.

In India barley is also grown during the winter half-year. The Middle Ganges is the most important producing region. Barley is

TABLE 27. BARLEY: ACREAGE, YIELD PER ACRE, PRODUCTION, AND PERCENTAGE OF WORLD TOTAL PRODUCTION IN SPECIFIED COUNTRIES — AVERAGES FOR THE FIVE-YEAR PERIOD 1930–31 TO 1934–35

Rank	*Countries*	*Acreage, in Millions of Acres*	*Yield, in Bu. per Acre*	*Production*	
				In Millions of Bu.	In Percentage of World Total
1	China	16.30	22.2	361.15	16.33
2	U.S.S.R.	18.22	16.0	290.85	13.15
3	Germany	6.04	35.9	214.33	9.69
4	United States	10.64	20.1	213.67	9.66
5	Japan and Chosen	4.44	26.8	119.24	5.39
6	Spain	4.68	23.8	111.34	5.04
7	India	7.57	14.6	110.46	5.00
8	Canada	3.94	19.1	75.20	3.40
9	Rumania	4.57	16.1	73.56	3.33
10	Turkey	3.59	19.4	69.85	3.16
11	Poland	3.00	22.1	66.40	3.00
12	Morocco	3.46	15.2	52.78	2.39
13	France	1.81	26.6	48.06	2.17
14	Denmark	.88	51.8	45.30	2.05
15	Great Britain	1.13	39.2	43.05	1.95
16	Algeria	3.35	10.6	35.38	1.60
17	Hungary	1.17	25.0	29.23	1.32
18	Argentina	1.21	22.5	27.10	1.23
19	Australia	.42	18.7	7.84	0.35
	All others	12.78	—	216.21	9.79
	World total	109.20	20.2	2,211.00	100.00

used both as food for man and a feed for animals. Barley production in India is more or less confined to the more humid regions; its distribution does not extend as far south as that of wheat, but very little of the crop is grown in the Deccan.

It is evident from Table 27 and also Fig. 71 that little barley is produced in the southern hemisphere. In Argentina and Australia wheat provides a more profitable export crop than barley; also in Argentina climatic conditions are more favorable to corn than to barley production.

Distribution of Barley in the United States. The production of barley is of less importance in the United States than that of either wheat or oats. Since production is evaluated in variable units of weight, bushels, it is necessary to state the production of the four important cereals in equivalent units such as millions of pounds. When this is done for the five-year period, 1930–31 to 1934–35, it is found that the United States produced annually 43,958 millions of pounds of wheat, 31,520 of oats, 10,256 of barley, and only 1,876 millions of rye. The percentage production of these cereals on the basis of world total shows the same relationship, namely 13.32 per cent for wheat, 12.71 for oats, 9.66 for barley, and 1.69 for rye. Barley is grown primarily for feed. For that purpose it comes into competition especially with corn, also with oats, and to some extent even with wheat. In many portions of the United States, corn is a more efficient producer of feed than barley. Barley is an important crop in the northern portion of the Corn Belt. The bulk of the crop is, however, produced north of the intensive corn growing sections; that is, where temperature conditions are less favorable to corn. The ecological optimum for corn is found in regions with moist, warm summers, the very set of conditions unfavorable to barley production. Barley, on the other hand, with its low temperature requirement and its ability to mature in a short physiological growing season, is found in the north and extends even into the steppe climates. Table 28 gives the statistical data of barley production by important producing states. Figure 72 gives the distribution of barley acreage.

The largest contiguous and most important barley producing area of the country extends from the western shore of Lake Michigan into the Dakotas. The eastern portion of this belt, that is, where the BC′r and CC′r climates prevail, is admirably suited to the

production of high-quality malting barley; in the drier CC′d climates, feed barley is grown. Because of variability in climate from season to season the line separating the malting from the feed barley producing sections is not distinct; however, as the plains area is approached an increasing acreage of Trebi is encountered. Maltsters generally object to this variety. Prime malting barley in this area is mostly of the Manchuria-Oderbrucker type which is grown

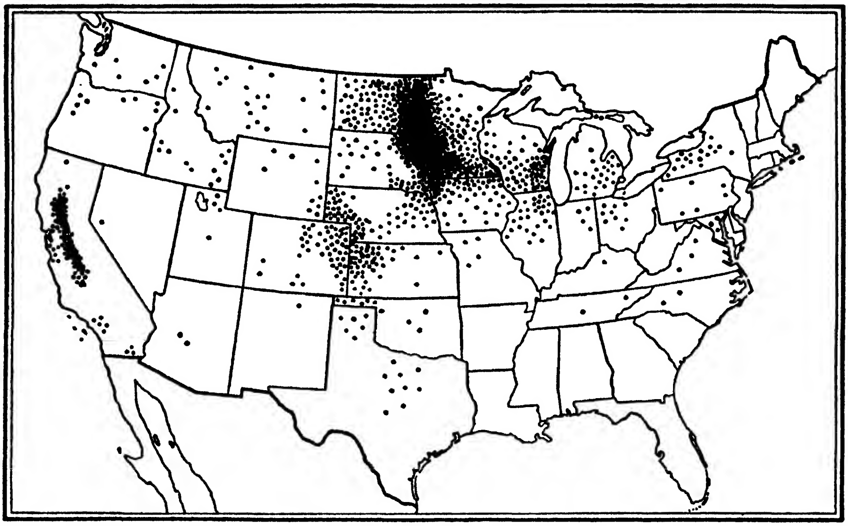


FIG. 72. Distribution of barley in the United States, average acreage harvested 1928–1937. Each dot represents 10,000 acres.

primarily in the eastern more humid portion of this area. Certain smooth awned varieties also produce barley suitable for malting purposes.

The extensive barley producing area of northwestern Kansas, southwestern Nebraska, and northeastern Colorado is interesting. The climate classifies as DC′d. In this area barley is largely second choice to wheat. As stated by Harlan (10), "if the wheat seeding is successful, wheat is grown. If for some reason the ground cannot be prepared for wheat, or if it is winterkilled, spring barley is sown as a catch crop." Barley matures slightly earlier than other spring cereals; as a matter of fact, in many seasons early varieties mature fully as early as winter wheat. Barley escapes drought more effectively than other crops.

Barley is an important feed crop in all of the irrigated valleys of the Rocky Mountain states. In parts of the area, as in the Columbia River basin and in the Palouse region, it is grown without irrigation.

Another outstanding barley producing area is found in the Sacramento and San Joaquin Valleys of California. Here also barley is grown in competition with wheat. The crop is sown in winter, December and January. The Sacramento Valley produces a prime grade of malting barley. The barley produced in the San Joaquin Valley is not so mellow as that produced in the Sacramento Valley and is therefore used mostly for feed. In the first area the climate is BC′s; in the second it approaches the warmer and drier CB′s climate.

TABLE 28. BARLEY: ACREAGE HARVESTED, PRODUCTION, AND PERCENTAGE OF UNITED STATES TOTAL PRODUCTION IN SPECIFIED STATES RANKED ACCORDING TO PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGES AND PRODUCTION EXPRESSED IN MILLIONS.

Rank	*States*	*Acreage Harvested*	*Production*		
			Average 1928–1937, in Bu.	Percentage of U. S. Total, 1928–1937	1938, in Bu.
1	Minnesota	1.98	44.09	18.92	48.02
2	California	1.09	29.55	12.68	27.55
3	North Dakota	1.85	28.95	12.42	21.32
4	South Dakota	1.45	25.25	10.84	29.24
5	Wisconsin	0.78	21.26	9.12	24.29
6	Iowa	0.54	13.73	5.89	13.63
7	Nebraska	0.65	11.88	5.10	21.53
8	Colorado	0.43	8.08	3.47	11.99
9	Illinois	0.28	7.29	3.13	4.05
10	Kansas	0.41	6.35	2.73	6.68
	All others	1.56	36.59	15.70	44.71
	Total U. S.	11.02	233.02	100.00	253.01

The production of winter barley is of local importance in the southeastern states and along the Pacific coast. The total acreage of the crop is small. Winter barley in that area is giving good results in providing fall and early spring pasturage. Etheridge *et al.* (8) regard it as the best pasture crop among the grains in central and southern Missouri. Barley is not so winter-hardy as wheat; its distribution to the north is therefore limited.

OATS

Commercial Importance. Oats are produced almost exclusively as a feed for livestock. They are mostly fed in the form of grain, but are also more extensively employed for the production of grain hay than any other cereal. Oats contain more crude fiber than the other cereals. This makes them bulky and of relatively low volume value. Most of the crop is fed on the farms where it is produced; its bulkiness, comparatively low value, and the limited industrial uses made of it discriminate against its entering into trade channels. Oats are relatively high in fat, protein, and mineral matter. This together with their bulkiness makes them a desirable feed for breeding stock and young animals.

Only around 3 per cent of the oat crop of the United States is milled or processed for human consumption. Oatmeal and other oat preparations are used as breakfast foods. Oatmeal crackers and oat bread are other food products.

Historical. The cultivation of oats is not so old as that of wheat or barley. The crop was unknown to the Ancient Egyptians, Hebrews, Chinese, and Hindus. The first mention of oats in literature is found in the writings of a Greek physician, Dieuches, living in the fourth century B.C. Common oats were evidently first cultivated by the ancient Slavonic peoples of eastern Europe during the iron and bronze ages. Plinius was familiar with the crop, designating it as *Avena graeca*, thereby inferring its introduction from Greece. Zade (29) indicates, however, that the oats mentioned by Plinius, Columella, and other Roman writers were not our common oats, *A. sativa*, but rather the cultivated red oats, *A. byzantina*. The cultivated red oats are still grown in the Mediterranean region and in other sections with warm climates. The Greeks apparently introduced them from Asia Minor, their probable place of origin. They used oats for the production of feed, for making porridge, and also for medicinal purposes. The Greeks apparently made greater use of oats as a food crop than the Romans who used them largely as feed for animals.

The place of origin of common oats is not known. Oats appear to have been the main cereal food crop of the German tribes at the time of Christ. Later their importance as a food crop decreased, except in times of need. The Celts also used oats extensively; even

at the present time they play a comparatively important part in human nutrition in Ireland, the Orkney and Shetland Islands, and Scotland.

Climatic Relationships. Oats are essentially a crop of moist temperate regions. The important oat producing areas of the world are found in the woodland, the Dfa, Dfb, Cfa, Cfb, and BC′r, BB′r, and CC′r climates, Table 29. Oats thrive in the marine and littoral climates. While not excluded from the interior of the continents, they yield decidedly less there and take a secondary place to wheat and barley. This is true especially in the warmer regions. They are not adapted to the steppe climates. Since oats demand a longer growing season than barley their distribution extends neither as far to the north nor to as high elevations as barley. The shortness of the season at higher latitudes and the advent of hot dry summers set the limits of oat production. Continental areas bordering on the steppe or located where high summer temperatures prevail produce early-maturing varieties; in addition to this the crop is sown as early as seasonal conditions permit so that the plants may develop during the cooler and also more humid portion of the season. Oats of the **sterilis** type, the red oats, are more tolerant to high temperatures than the common oats. This, together with the facts that the crop is sown early and matures in early summer, accounts for the production of oats of the **sterilis** type in the warmer regions such as the central and southern Great Plains area and the Mediterranean region. The northern expansion of oats in the Scandinavian countries and in Russia corresponds according to Engelbrecht, cited by Zade, with the September isotherm of 9°C (48°F). The southern limit of the crop coincides in Russia with the May isotherm of 15°C (59°F) and with the July isotherm of 21°C (70°F).

Fall-sown oats mature earlier than the spring-sown crop, thus enabling them to mature before the arrival of high temperatures. Oats are, however, less winter-hardy than either wheat or barley. This confines winter oats to areas with mild winters. Occasional depressions of temperature approaching 0°F are under most soil conditions fatal to fall-sown oats. Consequently the production of the crop is hazardous in areas where the temperature is likely to drop down to that point during the winter months.

TABLE 29. CLIMATIC RELATIONSHIPS IN THE IMPORTANT OAT PRODUCING AREAS OF THE WORLD

Producing Region	*Climatic Classification*			
	Relative Location	Vegetation	Köppen	Thornthwaite
Northeastern United States .	Trans.	Woodland	Dfa Dfb Cfa	BC′r CC′r BB′r
Northwestern Europe . .	Trans.	Woodland	Cfb	BC′r CC′r
Russia	Cont.	Woodland	Dfc	CC′r

Soil Conditions for Oats. Oats are less specific in their soil requirements than either wheat or barley. A favorable amount of nitrogen is essential to good yields. Excess nitrates, on the other hand, may cause serious lodging. Except on sandy soils oats respond less to phosphorus and potassium than other cereals. All soils with fair drainage well supplied with moisture are adapted to oat production; even rather light sandy soils will produce oats under favorable moisture conditions. Since oats are so easily satisfied as to their soil requirements they are often grown in the least favored place in the rotation, as after a heavy feeder like corn. The highest yields of oats are obtained on loamy and heavy soils that are retentive of moisture. Oats also do better on cold wet soils than other cereals. According to Mackie (15), "alkali and saline soils may, if the climatic conditions are favorable, produce crops of oats where wheat and barley would fail."

World Distribution of Oats. Table 30 gives the statistics of world oat distribution by countries, while Figures 73a and 73b give a comparison of the world's barley and oat acreages. It will be observed from both the tabulated data and the distribution map that oats are primarily a European and North American crop. But few oats are grown in the other continents. In this respect the distribution of oats is quite similar to that of rye with the exception that the oat crop is of much greater importance than rye in the United States and in Canada. In other words, oats are not so distinctly a European crop as is rye. The United States and Canada together produce 30.82 per cent of the world's oat crop as compared to only 2.17 per cent of the world's rye.

The production of oats in the United States will be discussed under a separate heading.

Oats rank second in total value among the grain crops of Canada as a whole, but in Ontario and the other eastern provinces they take first place by a large margin. The greatest volume of oats is produced in the prairie provinces; according to Derick (7) 62 per cent of the total Canadian oat crop in 1935 was produced in the provinces of Manitoba, Saskatchewan, and Alberta. This large volume of production in the prairie provinces should not be taken to mean that the oat crop is of relatively greater importance here than in the eastern and Maritime provinces. The large volume is accounted for by the great expanse of agricultural land in the prairie provinces with climatic conditions fairly favorable to the production of the crop. Only a small percentage of the Canadian oat crop is exported. During the ten-year period 1925–1934, the total export fluctuated between 2 and 34 million bushels. Most of the crop is grown for feed. The prairie provinces of Canada are far more important as producers and exporters of wheat than of oats.

Northwestern Europe represents the most intense oat producing area of the world. The reasons for this are found in the adaptation of the crop to the moderate and moist climate of this area, its leniency with regard to soil demands, and its wide employment as a feed crop. The high average yields of oats in all of this area and especially in Denmark, 71.9 bushels per acre, and in Great Britain, 60.3 bushels, attest the adaptation of the crop to the marine and littoral climates of the area. Since more feed can be produced on the better soils of this area from barley than from oats, there has been a significant shift from oats to barley in recent years. This is true especially on the heavier soils of central Germany. On the other hand, barley is unable to successfully compete with oats on the sandy soils of this humid area.

Some oats are grown in the Mediterranean and Balkan areas; the crop is, however, far less important in these areas than either wheat or barley, which are better adapted to the continental climates. In this area red oats take the place of the common oats of northwestern Europe.

Russia is an important oat producing country because of the vast areas available for the growing of the crop rather than because of intensive production. The average yields obtained are not high.

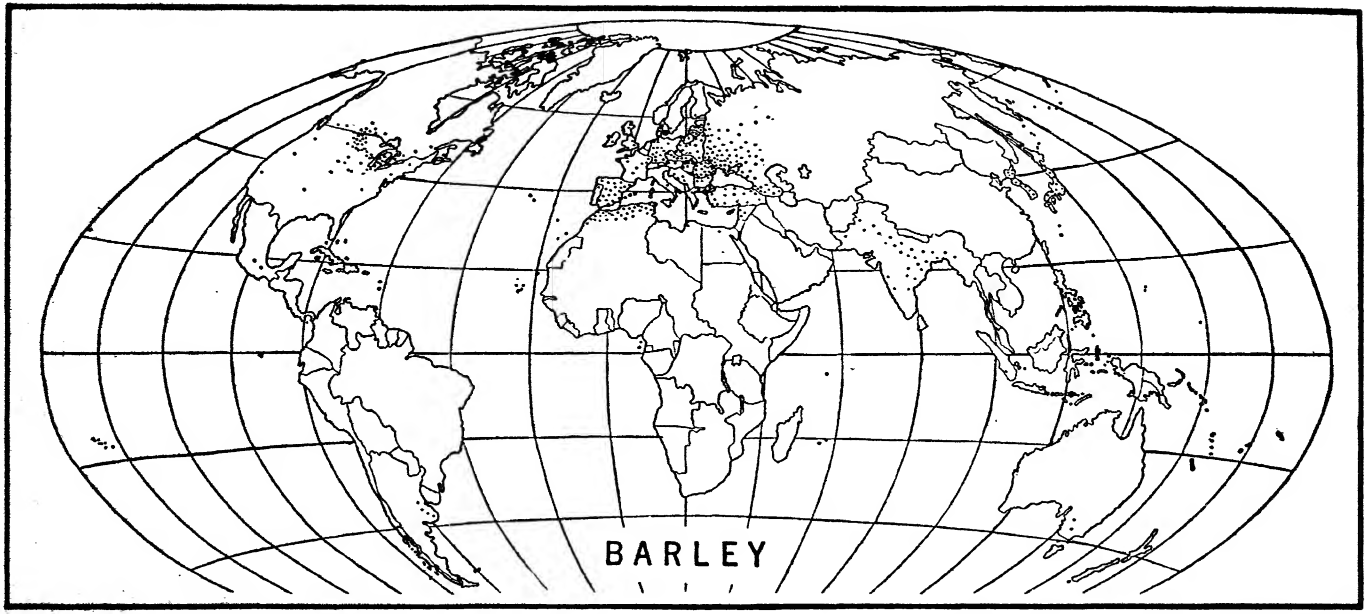


FIG. 73a. World distribution of barley acreage. Each dot represents 100,000 hectares (247,100 acres). Compare with Fig. 73b, showing world oats distribution. (After Kirsche.)

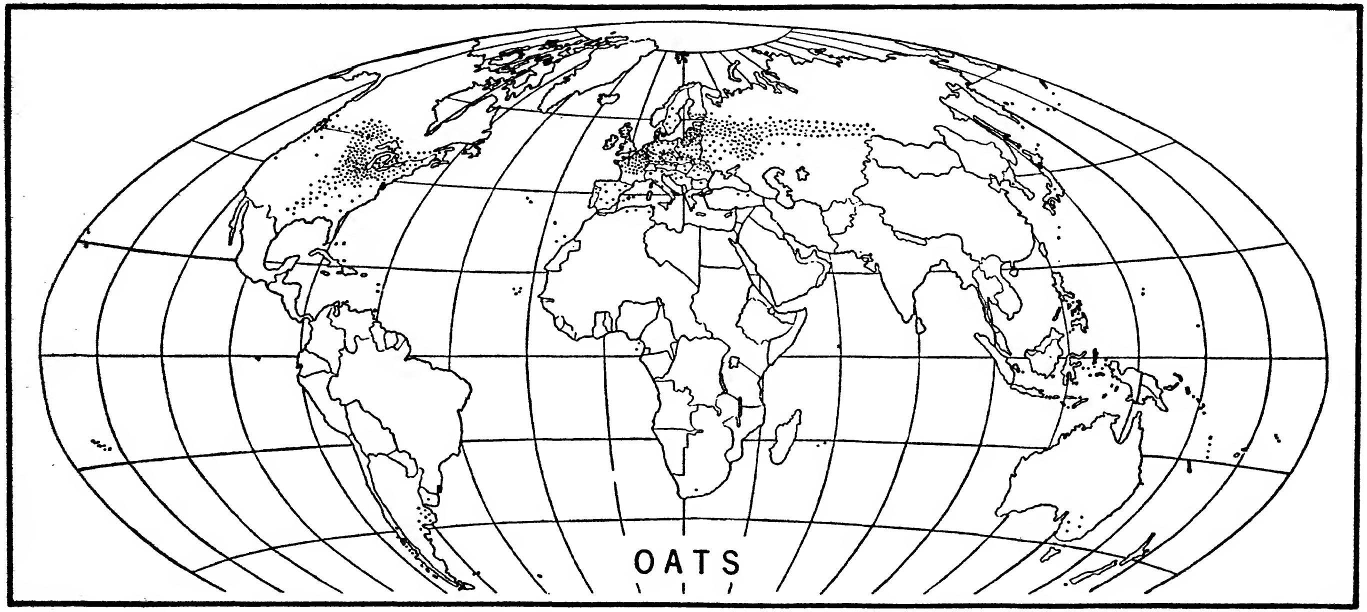


FIG. 73b. World distribution of oats acreage. Each dot represents 100,000 hectares. Compare with Fig. 73a, showing world barley distribution. (After Kirsche.)

The comparison of the distribution maps presented indicates that the oat crop of Russia is produced mostly in areas to the north of the important wheat and barley growing sections. The crop is grown primarily along the margin of the forested belt rather than on the grasslands; oats avoid the extremes of the steppe climates. In locations where the crop is grown near the grasslands early-maturing varieties capable of completing their cycles of development before the arrival of the heat and drought of summer are employed. This same condition is encountered in the plains areas of the United States; as a matter of fact many of the important varieties of oats produced in this and similar areas are of Russian origin or selected from varieties introduced from Russia. Varieties of Russian origin are also used in the oat producing areas of the Corn Belt where high summer temperatures dictate early maturity.

TABLE 30. OATS: ACREAGE, YIELD PER ACRE, PRODUCTION, AND PER CENT OF WORLD TOTAL PRODUCTION IN SPECIFIED COUNTRIES — AVERAGES FOR THE FIVE-YEAR PERIOD 1930–31 TO 1934–35

Rank	*Countries*	*Acreage, in Millions of Acres*	*Yield, in Bu. per Acre*	*Production* In Millions of Bu.	*Production* In Percentage of World Total
1	U.S.S.R.	42.25	23.9	1,007.74	23.27
2	United States	37.56	26.2	985.00	22.74
3	Germany	10.89	45.9	550.62	12.71
4	Canada	12.99	27.0	350.07	8.08
5	France	8.38	38.8	325.42	7.51
6	Great Britain	3.34	60.3	193.51	4.47
7	Poland	5.43	31.1	169.23	3.91
8	Sweden	1.62	48.3	78.37	1.81
9	Denmark	.95	71.9	68.51	1.58
10	Argentina	2.05	31.5	64.60	1.49
11	Rumania	2.18	24.3	52.90	1.22
12	Australia and New Zealand	1.20	33.1	24.47	0.56
	All others	15.46	29.8	460.36	10.65
	World total	144.30	30.0	4,331.00	100.00

Distribution of Oats in the United States. The distribution of the oat crop of the United States is determined by the climatic requirements of the crop, the ease with which it fits into established and recognized rotations, and the demand for it as a feed.

According to Finch and Baker (9) "the oat belt of the United

States consists of a crescent-shaped area extending from New England to North Dakota bounded on the north by the Great Lakes, and on the south and west by a curved line across central Ohio, central Illinois, eastern Nebraska, and thence northward along the Missouri River." This statement was written more than 20 years ago. Figure 74 gives the distribution of the oat acreage of the country for the years 1928–1937. The general distribution of the crop remains much the same.

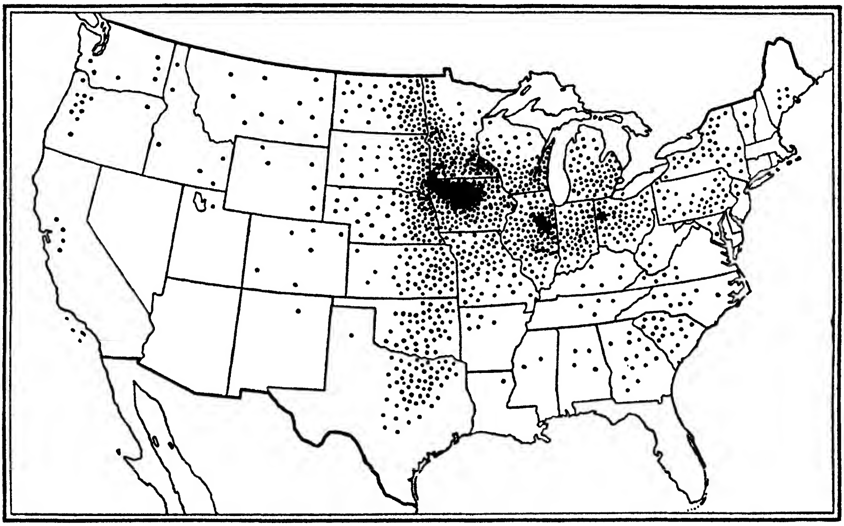


FIG. 74. Distribution of oats in the United States, average acreage harvested 1928–1937. Each dot represents 25,000 acres.

Table 31 gives the statistical data of oat distribution by important producing states. The great corn producing states are much in evidence in this tabulation. The northern Corn Belt is not only favored with climatic conditions suited to oats, but also provides a place for oats in the rotation; in addition to this it represents the most intensive livestock producing area of the country. Consequently the stage is more or less set for oat production.

Oats commonly follow corn in the rotation. In the northern portion of the Corn Belt the corn crop is frequently removed too late in the season for the seeding of winter wheat. The corn stalks remaining in the field also provide feed for livestock in the late fall months; it is therefore inadvisable to remove them to prepare the land for winter wheat. Since plowing is not necessary to prepare

the seedbed for oats the following spring, the crop can be seeded with but little expense. Oats are also frequently used as a nurse crop for clovers and grasses. In the southern portion of the Corn Belt, that is, in the corn and winter wheat region, winter wheat takes the place of oats in the rotation. Here the corn crop is removed from the field in time to seed winter wheat; furthermore, summer temperatures in this area are generally too high for best results with oats.

The importance of oats decreases sharply as the grassland areas of the Great Plains states are approached, and the crop is practically eliminated in the short-grass or steppe regions.

TABLE 31. OATS: ACREAGE HARVESTED, PRODUCTION, AND PERCENTAGE OF UNITED STATES TOTAL PRODUCTION IN SPECIFIED STATES RANKED ACCORDING TO PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGES AND PRODUCTION EXPRESSED IN MILLIONS.

Rank	*States*	*Acreage Harvested*	*Production*		
			Average 1928–1937, in Bu.	Percentage of U. S. Total 1928–1937	1938, in Bu.
1	Iowa	5.95	193.95	18.48	209.02
2	Minnesota	4.29	134.43	12.81	128.70
3	Illinois	3.95	125.12	11.92	111.67
4	Wisconsin	2.48	78.02	7.44	76.11
5	Nebraska	2.11	49.92	4.76	55.08
6	Indiana	1.75	49.18	4.69	34.06
7	Ohio	1.58	48.83	4.65	36.99
8	South Dakota . . .	1.68	41.22	3.93	46.92
9	Michigan	1.35	39.16	3.73	42.84
10	Missouri	1.62	34.74	3.31	46.51
	All others	10.69	254.73	24.28	280.53
	Total U. S.	37.45	1,049.30	100.00	1,068.43

An arm extends southward from the main oat producing area through eastern Kansas, Oklahoma, and into Texas. Oat production in this area is made possible by the employment of either very early-maturing varieties of common oats and to a greater extent by the use of early-maturing varieties of red oats. The red oats are often referred to as "warm climate" oats. That there is justification for this terminology is verified by Stanton and Coffman (23). The red oats are able to withstand hot dry weather, especially at heading and filling time, more effectively than the common oats.

In addition, the extreme earliness of some varieties of red oats often enables them to escape injury by hot weather and drought.

Oat production is of some importance in the Carolinas, Georgia, and Mississippi. A high percentage of the crop here is fall-sown. Some spring-sown red oats are also used. The other fall-sown oat producing areas of the United States are found in California, western Oregon, and western Washington. According to Salmon (20) the isotherm of 30°F for the months of January and February corresponds with the northern limit of winter oat production.

Oats are an important feed crop in all of the irrigated sections of the northern portion of the United States.

RICE

Commercial Importance. The relative importance of rice as a food crop has already been alluded to. The crop is of primary importance to the support of the teeming populations of the Orient. In the humid lands of the tropics rice has no competitor in its ability to support dense populations. This is well stated by Huntington (12) in the following paragraph.

> "Few plants except potatoes exceed rice in their capacity to support a large population on a small area. In Java, for example, the average yield per acre is something like 2,000 pounds of rough rice. If we make allowance for two or three crops per year, as well as for the parts of each grain not generally eaten by man, and if we remember that rice can be grown every year without exhausting the soil, it appears that Javanese rice land supplies four to six times as much food per acre as does wheat land in the United States. Similar, although less extreme, conditions prevail in China, Japan, India, and Egypt."

While rice is used for human consumption in nearly all parts of the world, its use for that purpose outside of the monsoon region of Asia and other moist tropical areas is of little importance in comparison with that of the bread cereals. Thus, according to Jones *et al.* (13), "the per capita consumption of rice in the continental United States is about six pounds a year, whereas in India, Chosen, French Indo-China, Java, Madoera, and the Philippines it is over 200 pounds, and in Japan proper, Taiwan, and Siam, from 300 to 400 pounds."

The different standards of living of the yellow and brown races as compared to the white race influence the relative importance of

rice in the diet of the former and wheat in the diet of the latter. A majority of the yellow and brown races live more exclusively on rice than any other people on any other single food crop. In France wheat plays a greater importance in the national diet than in probably any other country, yet, according to Zimmermann, this cereal furnishes probably less than 40 per cent of the total calories of the French diet, while in vast areas of Asia rice contributes as much as 80 to 90 per cent of the total food supply measured in calories.

Historical. Rice probably originated somewhere in the area extending from southern India to Cochin-China. A number of species of Oryza are found growing wild in the tropics of both hemispheres. The cultivated rice in all probability originated from one or more of these wild forms. The history of the plant goes back to the unknown past. Rice is reported to have been the most important cereal of China in 2800 B.C. Its cultivation spread from China and India to Egypt and North Africa centuries ago. It was grown in Italy in 1468, and introduced into the colony of South Carolina, probably from Madagascar, about 1685.

Climatic Relationships. Table 32 gives the climatic classifications of the world's important rice producing areas. The rice climates are characterized by high temperatures during the growing season, an abundance of moisture, and in most instances a high atmospheric humidity. These very conditions exclude other cereals, at least during the growing season of the rice crop. In some areas as in China and India wheat and barley may be grown during the

TABLE 32. CLIMATIC RELATIONSHIPS IN THE IMPORTANT RICE PRODUCING AREAS OF THE WORLD

Producing Region	*Climatic Classification*			
	Relative Location	Vegetation	Köppen	Thornthwaite
China	Trans.	Woodland	Cw	BB′w
India	Trans.	Woodland	Aw Cwg	AA′r CA′w
Japan and Chosen	Marine	Woodland	Cfa	BB′r
Java and Madoera	Marine	Woodland	Af′ Aw	BA′w
Louisiana	Marine	Woodland	Cfa	BB′r

cooler and drier portions of the year. To the climatic requirement must also be added an abundant supply of fresh water for irrigation. Rice fields are covered with water, usually when the plants are from six to eight inches high, and the ground is submerged under three to six inches of water until the crop is nearly mature. The production of the so-called upland rice is of limited importance. It is grown without flooding. A high rainfall during the growing season is essential for its development.

Soil Requirements. Rice is produced on a variety of soils. The outstanding requirement of the soil is the ability to hold water over the surface for a considerable period. Furthermore, the drainage features must be such that the flood water may be promptly removed prior to harvest. Where the crop is grown with the aid of power equipment the soil must provide a solid footing for such machinery. Rich alluvial soils with impervious subsoils are ideal for the crop.

World Distribution of Rice. The statistical data of world rice production are presented in Table 33. Figure 75, taken from Blankenburg (5), gives the geographical distribution of the crop. Both the tabulated data and the cartographical presentation bring out the importance of the monsoon areas of Asia in world rice production. Around 97 per cent of the world's rice crop is produced in the Far East.

Zimmermann calls attention to the fact that wheat is a "cheap" while rice is an "expensive" crop. That it costs more to produce rice than wheat cannot be denied. But, as Zimmermann points out, "a large portion of the world's rice crop is produced and consumed outside of the borders of price economy so that ordinarily, for a large number of rice eaters, the market prices of rice and wheat have little significance." The subsistence economy of the rice growing countries come definitely into play at this point.

> "Subsistence economy is governed by natural, principally climatic, considerations. Rice is the most prolific food crop which can be produced in the monsoon regions. In the second place, wide areas of continental Asia, especially of China, lie outside of the reach of transportation facilities by means of which wheat can be brought to them from the outside. Third, there is little or no alternative occupation for labor. Finally, throughout the world, dietary habits are among the most tenacious of all human habits."

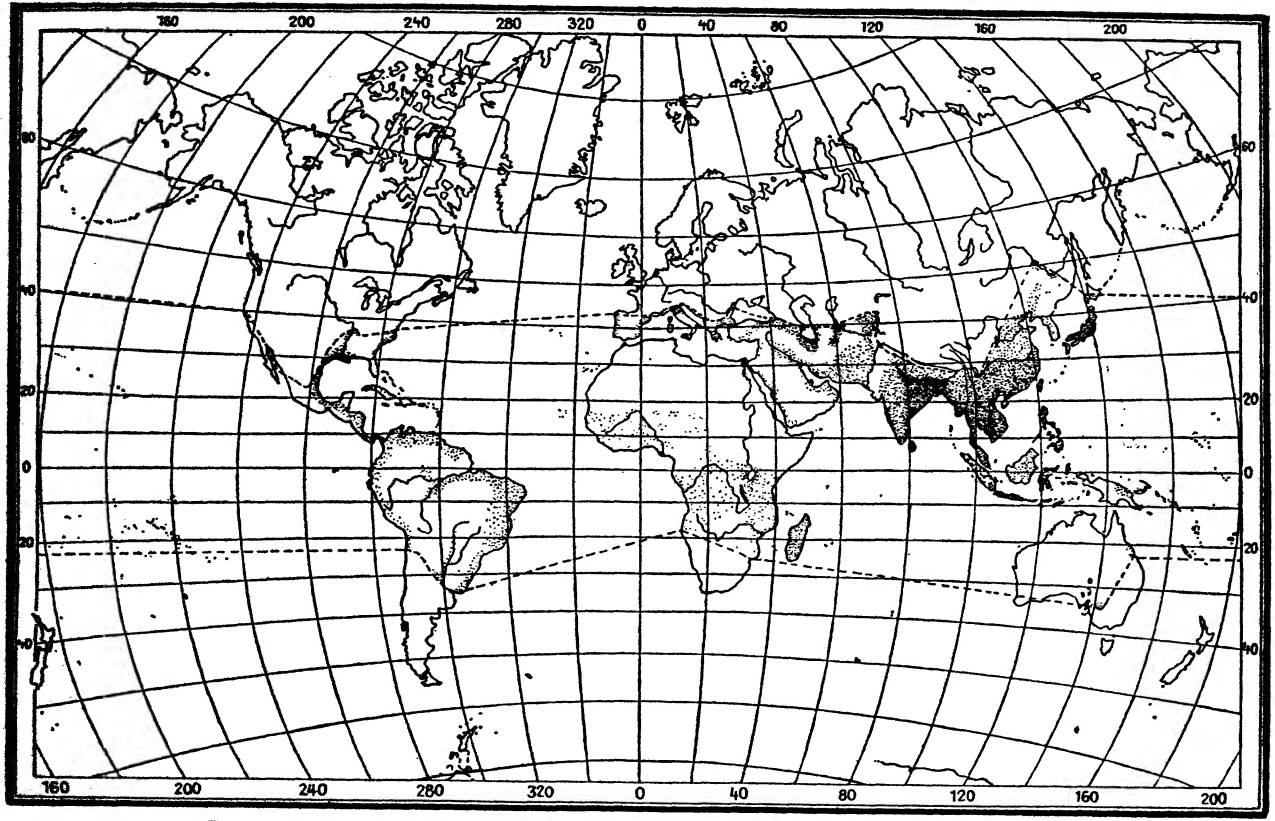


Fig. 75. Geographical distribution of world rice production. (After Blankenburg.)

The fact that China is the foremost rice producing country of the world does not mean that all the inhabitants of that vast country subsist on rice. That is not the case. To many Chinese, rice is a luxury; they subsist on the cheaper grains, such as wheat, millets, corn, and sorghums. Rice is an important crop only of the warmer and humid southeastern and eastern portion of the country. The important exporting countries are British India, French Indo-China, and Siam. Some rice is also exported from Italy, the United States, Egypt, and Brazil. Rice production in the extra-tropical countries is of local importance in the United States, Italy, Spain, Portugal, Bulgaria, and Yugoslavia.

TABLE 33. RICE: ACREAGE, PRODUCTION, AND PERCENTAGE OF WORLD TOTAL PRODUCTION IN SPECIFIED COUNTRIES — AVERAGES FOR THE FIVE-YEAR PERIOD 1930–31 TO 1934–35

Rank	Country	Acreage, in Millions of Acres	Production	
			In Millions of Lbs. of Milled Rice	In Percentage of World Total
1	China *	—	84,110	38.74
2	India	83.21	70,541	32.49
3	Japan and Chosen	12.00	24,597	11.33
4	Java and Madoera	9.16	8,164	3.76
5	French Indo-China	12.01	7,755	3.57
6	Siam	5.96	6,479	2.98
7	Philippine Islands	4.23	2,991	1.38
8	Taiwan	1.26	2,607	1.20
9	Brazil	1.03	1,638	0.75
10	United States	0.88	1,155	0.53
11	Madagascar	1.30	949	0.44
12	Italy	0.32	907	0.42
13	Egypt	0.35	622	0.28
14	Spain	0.12	404	0.19
	All others	—	4,191	1.94
	World total	—	217,110	100.00

* Official statistics for China are not available. The figure given is the estimate of the average production for the six-year period 1930–1935 expressed in terms of cleaned rice as presented by the Shanghai office of the Bureau of Agricultural Economics.

Distribution of Rice in the United States. It is evident from Fig. 76 that the production of rice is of only local importance in a limited number of areas in the United States. This is not surprising

in view of the climatic requirements of the crop. Table 34 gives the statistical data of rice distribution.

The rice-producing areas of the country have been subject to considerable shifting in the past 100 years because of the aftereffects of the Civil War and the utilization of power equipment on the extensive level areas in the central and western areas of production. Before the Civil War most of the rice crop of the United States was produced on the tidal lands of the Carolinas and Georgia. In 1839 South Carolina produced 70 per cent of the crop and Louisiana less than 4 per cent. By 1849 production had increased in

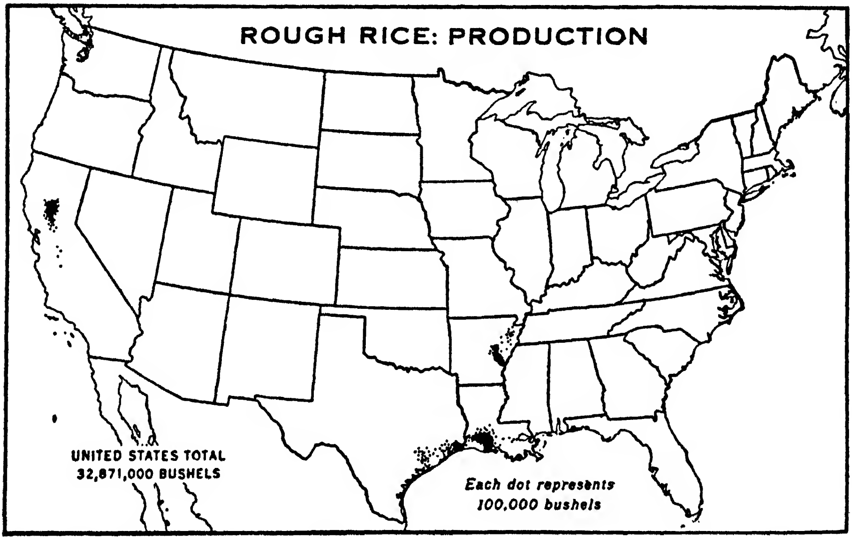


FIG. 76. Rice production in the United States in 1935. Each dot represents 100,000 bushels. (After Jones *et al.*)

Mississippi, Alabama, and Florida, but the Atlantic coastal areas still led in production. Even in 1859 South Carolina still produced more than 60 per cent of the crop, and 90 per cent of it was grown on the tidal lands of the South Atlantic states. The Civil War practically destroyed the rice industry of these states. In the period of 1929–1934 only around 8,000 acres of rice were produced in South Carolina and Georgia. Louisiana became the greatest rice producing state in 1889; it still holds this lead. From there the culture of the crop spread to southeastern Texas and to the prairie section of east-central Arkansas. Rice production is relatively new in California. The first commercial crop was grown in 1912. Most

of the crop is grown in the Sacramento Valley, with some production in the San Joaquin Valley.

TABLE 34. RICE: ACREAGE HARVESTED, PRODUCTION, AND PERCENTAGE OF UNITED STATES TOTAL PRODUCTION IN SPECIFIED STATES RANKED ACCORDING TO PRODUCTION — AVERAGES FOR THE TEN YEAR PERIOD 1928–1937 — AND THE 1938 PRODUCTION. ACREAGES AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	States	Acreage Harvested	Production		
			Average 1928–1937, in Bu.	Percentage of U. S. Total 1928–1937	1938, in Bu.
1	Louisiana	454	18,128	41.78	20,748
2	Texas	181	9,215	21.24	13,668
3	Arkansas	162	8,178	18.85	9,715
4	California	116	7,827	18.04	8,375
	All others	—	39	0.09	—
	Total U. S.	913	43,387	100.00	52,506

From 1926 to 1932 the United States exported from 20 to 25 per cent of its total production of milled rice. By 1935 only 10 to 12 per cent of the crop was marketed abroad.

REFERENCES

1. Baker, O. E., "The potential supply of wheat," *Econ. Geog.*, 1:24–27 (1925).
2. ———, and A. B. Genung, "A graphic summary of farm crops," *U. S. Dept. Agr. Misc. Pub.* 267, 1938.
3. Bennett, M. K., and H. C. Farnsworth, "World wheat acreage, yields and climates," *Wheat Studies of the Food Res. Inst.*, 8:265–308. Stanford University, 1937.
4. Bergsmark, D. R., *Economic Geography of Asia.* Prentice-Hall, New York, 1936.
5. Blankenburg, P., *Der Reis.* P. Funk, Berlin. Abstract and map in *Die Ernährung der Pflanze*, 30:116–117 (1934).
6. Carleton, M. A., *The Small Grains.* Macmillan, New York, 1916.
7. Derick, R. A., "Oats in Canada," *Dominion of Canada, Dept. Agr. Pub.* 554 (1937).
8. Etheridge, W. C., C. A. Helm, and E. M. Brown, "Winter barley, a new factor in Missouri agriculture," *Mo. Agr. Exp. Sta. Bull.* 353, 1935.
9. Finch, V. C., and O. E. Baker, *Geography of the world's agriculture.* Gov't Printing Press, Washington, 1917.

10. Harlan, H. V., "Barley: Culture, uses, and varieties," *U. S. Dept. Agr. Farmers Bull.* 1464, 1925.
11. Hughes, H. D., and E. R. Henson, *Crop Production.* Macmillan, New York, 1930.
12. Huntington, E., *The Human Habitat.* Van Nostrand, New York, 1927.
13. Jones, J. W., J. M. Jenkins, R. H. Wyche, and M. Nelson, "Rice culture in the southern states," *U. S. Dept. Agr. Farmers Bull.* 1808, 1938.
14. Kirsche, P., *Mensch und Scholle, Kartenwerk zur Geschichte und Geographie des Kulturbodens.* Deutsche Verlagsgesellschaft, Berlin, 1932. Abstracted in *Die Ernährung der Pflanze,* 32:350–352 (1936).
15. Mackie, W. W., "Oat varieties in California," *Calif. Agr. Exp. Sta. Bull.* 467, 1929.
16. Marbut, C. F., "Russia and the United States in the world's wheat market," *Geog. Rev.,* 21:1–21 (1931).
17. Morgan, M. F., J. H. Gourley, and J. K. Ableiter, "The soil requirements of economic plants," *U. S. Dept. Agr. Yearbook* 1938:753–776.
18. Percival, J., *The Wheat Plant.* Duckworth & Co., London, 1921.
19. Robertson, D. W., A. Kezer, F. A. Coffman, J. F. Brandon, D. Koonce, and G. W. Deming, "Barley in Colorado," *Colo. Agr. Exp. Sta. Bull.* 371, 1930.
20. Salmon, S. C., "The relation of winter temperature to the distribution of winter and spring grains in the United States," *Jour. Amer. Soc. Agron.,* 9:21–24 (1917).
21. Schindler, F., *Handbuch des Getreidebaus.* Paul Parey, Berlin, 1923.
22. Shollenberger, J. H., "Wheat requirements of Europe," *U. S. Dept. Agr. Tech. Bull.* 535, 1936.
23. Stanton, T. R., and F. A. Coffman, "Spring-sown red oats," *U. S. Dept. Agr. Farmers Bull.* 1583, 1929.
24. Strong, A. L., *The Soviets Conquer Wheat.* Holt, New York, 1931.
25. Timoshenko, V. P., "Russia as a producer and exporter of wheat," condensation by M. K. Bennett, *Wheat Studies of the Food Res. Inst.,* 8:277–369. Stanford University, 1932.
26. ———, *Agricultural Russia and the Wheat Problem.* Food Res. Inst. and Com. on Russian Res. of the Hoover War Library. Stanford University, 1932.
27. Whitbeck, R. H., and V. C. Finch, *Economic Geography.* McGraw-Hill, New York, 1924.
28. Woodward, R. W., and D. C. Tingey, "Barley variety tests in Utah," *Utah Agr. Exp. Sta. Bull.* 261, 1935.
29. Zade, A., *Der Hafer.* Gustav Fischer, Jena, 1918.
30. Zimmermann, E. W., *World Resources and Industries.* Harper, New York, 1933.

Chapter XXIII

THE COARSE CEREALS

CORN

COMMERCIAL IMPORTANCE

The Great American Feed Crop. Since the United States produces about 50 per cent of the world's corn crop, it is fitting to consider the commercial importance of corn in this country before discussing it as a crop of world importance. Corn is referred to by Jenkins (11) as the backbone of American agriculture. It represents the leading crop of the United States in acreage as well as in value of product. In 1929 corn occupied 27.0 per cent of all crop land in the United States as compared to 18.7 per cent for hay, 17.1 per cent for wheat, 11.9 for cotton, 10.1 for oats, 3.6 for barley, and 2.2 per cent for sorghums (Baker and Genung, 4).

According to Taylor (24), half of the corn crop of the United States is fed to hogs, and probably more than 90 per cent of it is fed to animals. Most of the crop is fed on the farms where it is produced. "Nearly 60 per cent of the hogs and pigs in the United States are in the Corn Belt, 14 per cent are in the Cotton Belt, and 11 per cent in the Corn and Winter-Wheat Belt." Around 25 per cent of the beef cattle of the country are found in the Corn Belt. The Corn Belt also has a dense population of dairy cattle, sheep, and poultry. It is not necessary to present statistics on these points. It is sufficient to say that the livestock industry of the United States is closely associated with corn production. Figure 77 gives the distribution of the corn acreage of the United States.

Corn is not only the outstanding grain feed crop of the United States; it is also the foremost silage crop. The acreage of corn cut for silage, however, constitutes but a little more than 4 per cent of the total corn acreage. Only 6 per cent of the total crop is cut solely for fodder.

Corn as a Food Crop. According to Leighty *et al.* (12), about 10 per cent of the corn crop of the United States was used for human food in the period 1912–1921. Since that time, there has been a decline in the domestic use of corn meal, corn flour, hominy, corn breakfast cereals, and corn starch for food purposes. On the other hand, Taylor (24) is inclined to the view that the use of corn oil and glucose is on the increase. The supplanting of home baking by commercial baking served to reduce the use of corn bread.

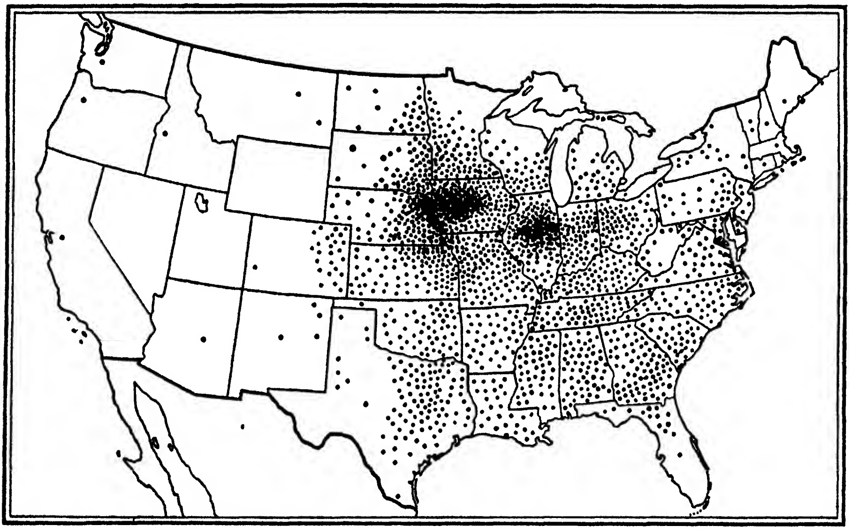


Fig. 77. Distribution of corn in the United States, average acreage harvested 1928–1937. Each dot represents 50,000 acres.

In the United States, Europe, and Argentina corn is grown primarily as a feed crop. In many producing areas of the world, notably in China, India, and Mexico, a high percentage of the crop is used for direct human consumption. The Balkan States also utilize a fairly high amount of corn for direct human consumption.

Sweet corn and pop corn are grown almost entirely for human use.

Industrial Uses. In the neighborhood of 75 million bushels of corn are used annually by the corn refining industry in the United States. The main products are starch, dextrins, corn syrup, corn sugar, and corn oil. Close to 2½ billion pounds of corn and corn products are used annually in the manufacture of fermented malt liquors, distilled spirits, and ethyl alcohol.

The possibilities of finding a greater use for "industrial alcohols" are being investigated with increasing interest at the present time with the double objective of creating a profitable and stable outlet for surplus agricultural commodities, and from the standpoint of conservation of natural resources. Jacobs and Newton (10) discuss the economic possibilities of using alcohol as a motor fuel. Corn, being the foremost carbohydrate producing crop in American agriculture, comes definitely into consideration in this respect.

HISTORICAL

Origin of Corn. Corn represents a distinct contribution of the Americas to the agriculture and food resources of the world. According to Mangelsdorf and Reeves (15), corn (*Zea mays*) originated from a remote Andropogonaceous ancestor in the lowlands of South America. The genus *Tripsacum* is supposed to have originated from the same ancestor. Thus, according to Mangelsdorf and Reeves, "had *Tripsacum* been more promising as a food plant we may be reasonably certain that there would have been two Maydeaceous cereals in America instead of only one. . . . Both *Zea* and *Tripsacum* proceeded along parallel evolutionary paths, so far as monoecism is concerned. Both exhibited a tendency to separate the sexes and to concentrate the staminate flowers in the terminal inflorescences and the pistillate flowers in the lateral ones. But here the similarity ends, for while *Zea* confined itself to, or became reduced to, a single species and remained a plant with low chromosome numbers and an annual habit of growth, devoting most of its energies to reproduction for seed, *Tripsacum* became a freely speciating genus, increased its chromosome number, assumed a perennial habit, and began to devote much of its energy to survival by the storage of food materials in the roots. Maize became more and more restricted in its range and was confined to extremely favorable sites scattered through the tropical forests, and was indeed probably on the road to complete extinction when man appeared on the scene. *Tripsacum*, in contrast, continued to spread until it had invaded regions formerly occupied by continental ice-sheets."

The original maize was probably podded. Even with its small seed completely enclosed in glumes, it was by far the best cereal

plant available. When the mutation from pod corn to naked corn occurred, it made a cereal even better suited to the needs of man. There is no way of determining whether this mutation occurred first in the lowlands or after maize had been carried by man into the Andean region. The next improvement of the plant brought about either by natural or by human selection in a man-made environment was in the shortening of the lateral axis or an increase in the length of the leaf sheaths, or both, to the point where the lateral inflorescence, the ear, was completely enclosed by the husk.

The Andean maize was in the course of time carried to Central America where it came in contact with *Tripsacum*. These two genera had become so divergent that hybridization was difficult. But a hybrid between these two plants apparently occurred. This hybrid, by repeatedly backcrossing with maize, resulted in the production of a new maizelike plant, later to be known as a separate genus, *Euchlaena*, or *Teosinte*. Being closely related to maize, *Euchlaena* hybridized freely with maize. Thus, in the words of Mangelsdorf and Reeves,

> "the original hybridization of *Zea* and *Tripsacum* and later repeated hybridization of the new genus, *Euchlaena*, with its maize parent resulted also in the transfer of some *Tripsacum* genes to the genetic complex of cultivated maize. This gave rise to some new types of corn previously not in existence, including the North American pointed pop corns, the dent corns, and the long, slender, straight-rowed flint and flour corns, types which are not represented in the Peruvian pottery and which even today are still unknown in the Andean region."

The Spreading of Corn Culture. Corn was first cultivated in the Andean region, from where its culture spread to Central and finally to North America. The ancient civilizations of Peru, Central America, and Mexico were based upon the culture of corn. Corn was unknown to Europe and Asia before the discovery of the Americas. Its culture even in northern and eastern North America is comparatively recent. Corn culture is reported to have reached the Rio Grande around 700 and Maine around 1000 A.D.

Corn was carried to Spain soon after the discovery of America, where it was grown for a time as an oddity in gardens. The possibilities of the plant as a field crop were, however, soon recognized, and it spread from Spain to France and Italy. Burtt-Davy (7) credits the Portuguese voyagers for the early and rapid introduc-

tion of maize into India, China, Cochin, and other parts of the East Indies. Another route of introduction into Asia appears to have been by way of Turkey, Arabia, or Persia. The exact date of introduction of maize into Africa is not known, but apparently the Portuguese also carried it into that continent. This, brings out Burtt-Davy, is suggested by the African's word for corn "mielie" which is undoubtedly a corruption of the Portuguese word *milho*, meaning grain. Among the native tribes of Africa the newly introduced maize was used to replace the ancient cultivation of millet. Corn reached the East Indies soon after the establishment of the Portuguese settlements there by Vasco da Gama at the beginning of the sixteenth century. Mendoza, cited by Burtt-Davy, mentioned maize as one of the plants observed by him in China as early as 1585. Corn apparently reached the Balkan States by way of Turkey. It is often referred to there as well as in other parts of Europe as "Turkish wheat."

CLIMATIC AND SOIL RELATIONSHIPS

Temperature Conditions. The southern origin of corn is reflected by its relatively high temperature requirements. For best results with the crop the growing season should be 140 or more days in length with a mean summer temperature of around 75, and with night temperatures exceeding 58°F. According to Finch and Baker (8), "practically no corn is grown where the mean summer temperature is less than 66°, or where the average night temperature during the three summer months falls below 55°." These temperature requirements set definite limits to corn production. There is, on the other hand, a significant difference in the temperature demands of different varieties; some may be grown in a season of less than 100 days, while other late-maturing types require a growing season of 180 days and a mean summer temperature of 80°F. The small grains replace corn in sections with short and relatively cool growing seasons. Under such conditions they are more productive than corn. This accounts for the rather sharp decrease in corn production north of the Corn Belt in the United States and also for the virtual exclusion of corn in the agriculture of northwestern Europe. The growing of corn for the production of fodder or silage extends into cooler regions than for strictly grain production.

Most of the important corn producing areas of the world are characterized by relatively high summer temperatures with fairly warm nights. That corn avoids cool climates is evident; nevertheless, the importance of warm nights to corn production can be overemphasized. Apparently the mean temperature during the growing seasons is of greater importance than the low point attained at night. Obviously, the night temperature enters into the calculation of the mean. In this connection Wallace and Bressman (29) make the observation that

> "it is a common belief that corn will not grow satisfactorily in regions where the nights are cool, although the days are warm. Usually the true explanation why corn is not grown in such sections is something else. In South Africa, where corn growing has expanded at a phenomenal rate since 1900, the minimum temperature at night during the tasseling season averages only about 60 degrees, and in some sections it is as low as 50 degrees. Cool nights reduce the rapidity of growth previous to tasseling, but if the season is long, there is no definite proof that cool nights (55 to 60 degrees at the low point of the night) reduce the yield."

It is necessary to point out that the slowing up of the rate of growth occasioned by cool nights would be highly detrimental to corn in many areas and especially in places where the physiological growing season is cut short by either low temperatures or the occurrence of droughts.

While the small grains take the place of corn in the cooler regions or where the growing season is short, the corn crop is ideally adapted to take fuller advantage of long and relatively warm growing seasons than the small grains, provided that moisture conditions are favorable. In other words, the corn crop is preeminent in the agriculture of the Corn Belt by virtue of its ability to utilize the physiological growing season to its fullest extent, whereas the small grains make use of only a part of the season suitable for growth.

Moisture Conditions. The moisture relationships of corn production were discussed in detail in Chapter XV. Special attention was given to the critical period in corn incident to tasseling and fertilization and to the comparative drought resistance of corn and the sorghums. While the corn plant has a high efficiency of transpiration, it is nevertheless very specific in its moisture

requirements, especially at the above indicated critical period. In considering the water requirements of corn it is well to keep in mind that the amount of dry matter produced per acre brings about a heavy demand for water, and, as is pointed out by Morgan *et al.* (19), corn "must obtain water from the soil during the period of its most rapid growth at a faster rate than any other field crop of the region." A marked summer concentration of rainfall or availability of moisture is therefore essential to high production. While corn makes specific moisture demands during its grand period of growth, the crop is very conservative in the use of water during its early phases of development. This is due in part to the small leaf surface exposed by the crop per unit of land area occupied and also to the fact that the crop is cultivated, that is, the plants are spaced, and in addition competing plants, weeds, are removed so that the moisture in the soil may be stored for future use.

General Climatic Regions. The bulk of the corn crop of the world is grown in climates transitional between marine and continental and in sections either with distinct woodland climates, or with climates transitional between woodland and grassland. The crop does not entirely avoid either strictly continental or grassland climates. Production in the extremes of these climates is, however, limited. Thus corn is grown to a limited extent in the steppe climates of the Great Plains area of the United States, in the steppe regions of Argentina, South Africa, Rumania, and southern Russia. In such areas wheat and barley are of greater relative importance than corn on account of the specific moisture demands made by corn during midsummer, that is, at a time when the small grains have completed their cycles of development. To some extent the detrimental effects of the dry summers of these climates are avoided by the growing of early-maturing varieties. On the other hand, corn is an important crop in areas where the native vegetation consisted largely of tall grasses, which after all is an index of rather favorable moisture conditions.

Table 35 gives the climatic types of the world's important corn producing areas. It will be observed that the range of climatic types encountered is great, from Af to BSk and AA′r to Cb′d. The ecological optimum for corn is found in the Dfa, Cfa or BC′r, CC′r, BB′r, CB′r climates. This emphasizes the fact that corn demands fairly high summer temperatures and above all favorable moisture

conditions during the later part of the summer. While the production of the crop extends into regions with the dry BSk or CC′d and CB′d climates, the yields obtained in such areas are low and variable. One of the main reasons for growing corn in such dry areas is that the crop fits well into the system of crop rotation employed. Corn fills the need for a cultivated crop; it leaves the soil in good condition for the winter or spring cereals to follow it in the course of rotations. Since corn is a cultivated crop, the necessity for plowing preparatory to the seeding of the cereals is eliminated.

TABLE 35. CLIMATIC TYPES IN THE IMPORTANT CORN PRODUCING AREAS OF THE WORLD

Region	*Climatic Classification*	
	Köppen	Thornthwaite
United States	Dfa, Cfa, Dfb, BSkw	CB′r, CC′r, BB′r, CB′r CC′d, CB′d
Balkan States	Cfx, Dfc, BSk	CB′r, BB′d, CC′r, BC′r CB′d
Southern Russia	Dfb, BSk	CC′r, CB′d
Argentina	Cfx, Cfa	CB′r, BB′r, CB′w
China	Cfa, Cw, Dwa	BB′w, CB′w
East Indies	Afwi	AA′r
South Africa	Cw, Awi	CB′d, CB′w

Soil Conditions for Corn. Corn is grown on a great variety of soils. Fair drainage is essential; poorly drained soils are too cold in spring. Furthermore, corn demands good soil aeration. Corn grows successfully over a wide range of soil reaction, *p*H 5 to 8, although yields are usually adversely affected by degrees of acidity represented by *p*H values of less than 5.5. Corn requires not only an abundance of moisture but also an abundance of readily available plant nutrients during its period of rapid growth in late summer. Nitrates are especially in demand at that time. The close relationship between an available supply of nitrogen and corn yields has already been discussed in Chapter XXI. Corn also requires a fair supply of phosphorus. A deficiency in this element is especially reflected in a slow initial growth.

The Corn Belt of the United States is favored with not only suitable climatic but also with soil conditions well adapted to the

production of corn. This is well stated by Morgan *et al.* in the following paragraph.

> "Of the zonal, or great soil groups, the Prairie soils are inherently the best suited for corn, since they fulfill its requirements most completely and are developed in the region in which the climate is especially favorable. It is no mere accident that the Corn Belt, although more extensive geographically, centers about the Prairie soils, extending from western Indiana to eastern Nebraska. Here the climate and grass vegetation have been largely responsible for the exchangeable bases. The benefits of the relatively high content of organic matter, such as tilth, water-holding capacity, and available nutrients, are well known and scarcely need further comment. The dark color of the surface of these soils of the grasslands also promotes to some degree a desirable soil temperature."

DISTRIBUTION OF CORN

World Distribution. The statistical data of world corn distribution are presented in Table 36. Figures 78 and 79 give a cartographical view of the locations of the corn producing areas of the world. Though the producing areas are widely scattered, the specific climatic requirements of the crop confine it to a limited number of heavy producing areas. Corn production, for instance, is not distributed over the globe as generally as the production of wheat. The other significant fact that is evident from the tabulated data and also from the figures showing world distribution is the concentration of the world's corn acreage and production in the United States. For the five-year period 1930–31 to 1934–35, this country produced roughly 50 per cent of the world's corn crop.

Corn production in the United States reached its peak in 1920. The corn crop of this country for the period 1900–1920 averaged 68 per cent of the world crop, fluctuating from 59.9 to 73.4 per cent. Since the first World War, the United States has been losing some of its leadership as a corn producer. Shepherd *et al.* (22) show "that the world production of corn has remained roughly constant during the past 20 years; the decline in the relative position of the United States has been the result of a decline in the production of corn in the United States and a compensating increase in other countries." A number of factors have entered into the decline of corn production in the United States in recent years, among which may be mentioned: a series of years of drought

in the western portion of the Corn Belt; a growing realization of the necessity for proper land use to reduce soil erosion losses — corn, being an intertilled crop, must be handled with care on sloping lands or grown in rotation systems planned to reduce soil

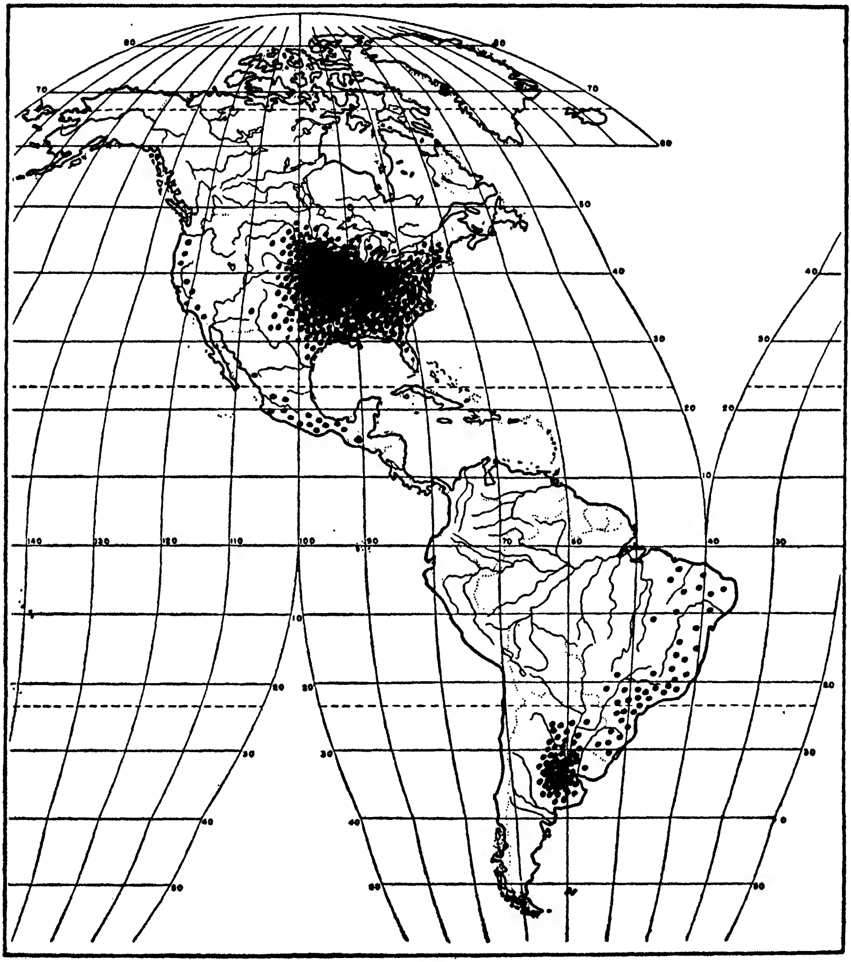


FIG. 78. Distribution of corn in the western hemisphere. Average production of the five-year period 1930–31 to 1934–35. Each dot represents 5 million bushels.

losses to a minimum; the greatly reduced demand by foreign countries for American-produced pork products, or more correctly stated the inability of foreign countries to purchase or exchange goods for pork products produced in the United States; and lastly the AAA production control program instituted in 1934.

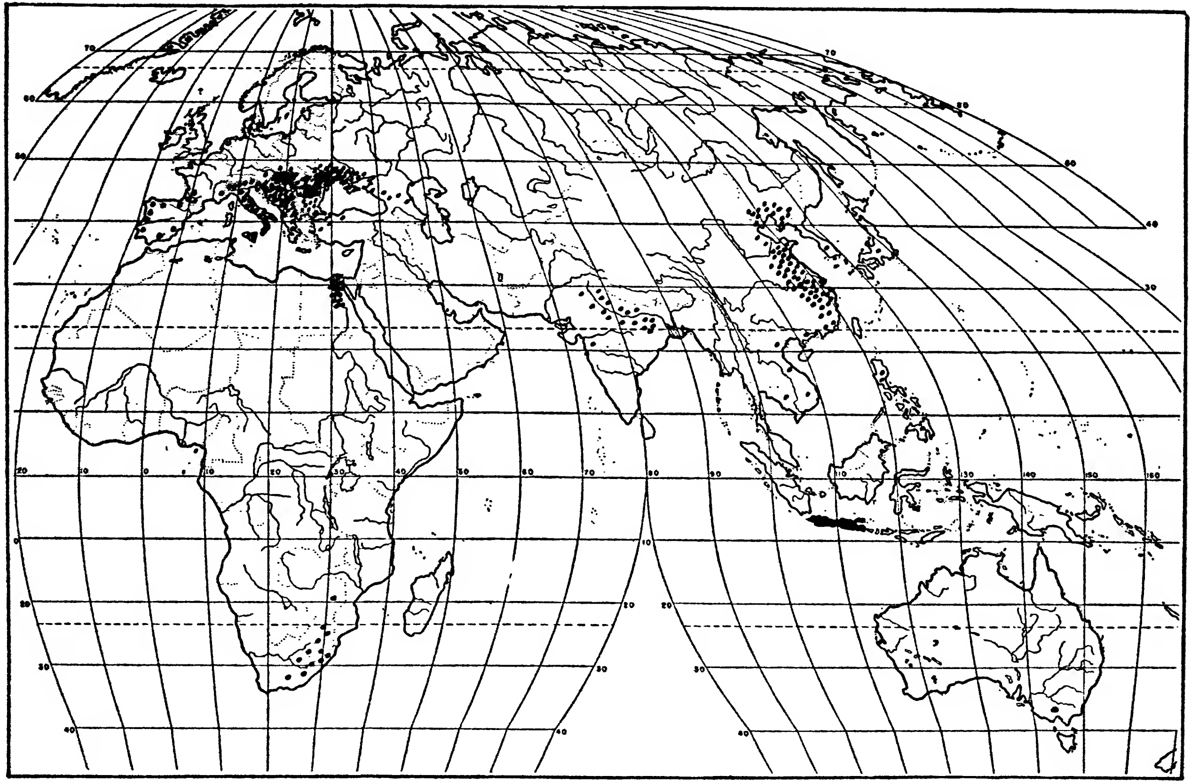


FIG. 79. Distribution of corn in the eastern hemisphere. Average production for the five-year period 1930–31 to 1934–35. Each dot represents 5 million bushels.

While the relative importance of the United States as a world producer of corn has decreased somewhat during the past decade there is no reason to believe that this country will lose its eminent position as a producer of corn. Even with the reduction in the size of the corn crop and increases in production in other countries the United States is still far ahead of any competing country. Furthermore, the United States contains far greater expanses of land with favorable conditions of both climate and soil than any other country or any other section of the world. As a matter of fact, while the production of corn in other countries can be intensified, the acreage available for corn production in all countries having territories suitable for the purpose is at the present time quite well occupied either by corn or by crops grown in direct competition with corn. Possible exceptions to this may be found in undeveloped areas of Brazil and in limited sections in the humid portions of Africa. The tabulation of climatic types prevailing in certain areas now producing corn, indicated in Table 35, brings out the fact that some of the crop is being grown in decidedly moderate and even minimal areas. Further expansion in such areas will not be possible. This indicates that possible future increases in corn production will take place largely through the adoption of improved methods of handling the crop, especially in the optimal and moderate areas, rather than through significant expansion of acreages.

The corn producing regions of the western hemisphere, Fig. 78, may be classified into three areas, namely, the eastern portion of the United States, Mexico, and the Argentine-Brazilian areas.

The distribution of corn in the United States will be presented under a separate heading.

Argentina ranks next to the United States as a producer of corn. The country has the distinction of being the world's most prominent exporter of corn. Around 80 per cent of the crop is grown for export. During the five-year period 1929–30 to 1933–34 the United States produced over eight times as much corn as Argentina; the latter, however, outranked the United States 40 to 1 as a corn exporting country. The great importance of Argentina as a corn exporting country is brought out by the fact that over 70 per cent of the world trade in corn originated in that country for the period indicated above. In 1936 Argentina exported 330 million

bushels of corn. Its nearest rival was Rumania with 30 million bushels.

TABLE 36. CORN: ACREAGE, YIELD PER ACRE, PRODUCTION, AND PERCENTAGE OF WORLD TOTAL PRODUCTION IN SPECIFIED COUNTRIES — AVERAGES FOR THE FIVE-YEAR PERIOD 1930–31 TO 1934–35

Rank	Country	*Acreage, in Millions of Acres*	*Average Yield, in Bu. per Acre*	*Production*	
				In Millions of Bu.	In Percentage of World Total
1	United States	103.45	22.1	2,289.61	49.85
2	Argentina	10.94	31.0	339.12	7.38
3	China *	11.07	21.9	242.81	5.29
4	Brazil	9.54	22.6	215.37	4.69
5	Rumania	11.76	17.4	204.53	4.45
6	Yugoslavia	6.18	25.7	158.99	3.46
7	U.S.S.R.	9.42	16.3	153.39	3.34
8	Italy	3.60	30.1	108.18	2.36
9	India	9.17	9.7	89.28	1.94
10	Java and Madoera . . .	4.96	15.3	76.08	1.66
11	Hungary	2.77	26.4	72.94	1.59
12	Mexico	7.84	9.2	71.94	1.57
13	Egypt	1.88	36.6	68.82	1.50
14	Manchuria	2.60	26.1	67.77	1.48
15	Union of South Africa . .	5.87	—	61.47	1.34
—	Australia **	0.28	25.7	7.15	0.16
	All others	20.57	—	365.55	7.94
	World total	221.90	—	4,593.00	100.00

* Four-year average only.
** Not in rank but given for sake of comparison.

The area suitable for corn production in Argentina, especially the area with optimal conditions, is limited. Much of the country is either too dry or too cold. Two provinces, Buenos Aires and Santa Fe, contain 76 per cent of the corn acreage of the country. Yields fluctuate materially from year to year, chiefly because of extreme variations in rainfall. In certain sections rather frequent attacks of locusts also constitute a menace to the crop. On the other hand, in the rather limited optimal area conditions are very favorable to the production of corn. Of these areas Spafford (23) writes,

"It is difficult to imagine better maize-growing conditions than exist over an area approaching a couple of hundred of millions of acres in Argentina, for here are to be found very fertile, free-working, chocolate

coloured soils, from 1 foot to 2 feet in depth, resting upon sufficiently well-drained subsoils to prevent waterlogging, and receiving from 25 in. to 45 in. of average annual rainfall, of which 85 per cent to 95 per cent is distributed fairly evenly throughout the spring, summer, and autumn months."

This statement appears to be somewhat optimistic with regard to the acreage available and in view of the extreme annual fluctuations in Argentine corn production. Hughes and Henson (9), for instance, point out that "the bulk of the cropped land in Argentina corresponds more closely to the area of the Great Plains than to that of the Corn Belt." Apparently much of the Argentine corn producing area must be classified as moderate or even minimal. The high average yield for the country for the period covered in Table 36 is accounted for by the great concentration of the crop in the rather limited optimal area. The Argentine corn crop is grown in competition with wheat, alfalfa, and flax.

Corn production in Brazil has been increasing. Any great expansion of the crop in this country is precluded by lack of level expanses of land suitable for corn production. None of the crop is available for export; a high percentage is utilized for human consumption.

The production of corn is of great local importance in Mexico. Here also the crop is grown largely for human use. The fields are generally small, and rather primitive methods of culture are employed. The yields, as indicated in Table 36, are very low.

The distribution of corn in Europe serves to emphasize the high temperature requirements of the crop. Production is almost entirely confined to the southern portions of the continent, extending from Italy and Hungary across the Balkan States and into southern Russia. Much of this area has a summer deficiency of rainfall, which accounts for the relatively low yields in Rumania and southern Russia. The most intensive area of production is found in Hungary and portions in Rumania, Bulgaria, and Russia. Michael (16, 17, and 18) points out that increased acreage and production of corn especially in Hungary and also in Yugoslavia and Rumania is probably an after-effect of the land reforms instituted in these countries after the first World War. The breaking up of large estates and corresponding increases in peasant agriculture resulted in decreased emphasis on the production of wheat

and barley for export and on oat production in connection with horse breeding. More emphasis is now placed on the growing of corn and swine production. In certain sections of the Balkan States a relatively high percentage of the corn crop is used for human consumption. Rumania is the only country producing any appreciable quantity for export.

It is interesting to note an increase in corn production in parts of central Europe. Becker (5) points out an increase in the corn acreage of Germany from 5,495 to 125,000 acres between 1932 and 1937. This author brings out that more feed can be produced per unit of area with the employment of corn than with oats when proper attention is given to the selection of varieties and when the crop is produced under conditions of intensive culture.

Corn is a crop of considerable importance in China and Manchuria, also in the East Indies and in India. In the East Indies corn is especially important in Java and Madoera. A high percentage of the crop is used for human consumption. French Indo-China exported 18.5 million bushels of corn in 1936.

In Manchuria (Manchukuo) corn is grown under rather severe conditions as to temperature and moisture relationships. It is grown only in the most favored areas, yielding its place to kaoliang and millet in the less favored regions.

China is a great producer of corn. Moisture and temperature conditions are generally favorable. The corn is often interplanted with soybeans. The crop is grown in the eastern humid areas of the country.

Corn is a relatively unimportant crop in India. According to Bergsmark (6), corn occupies less than 3 per cent of the cropped land of the country. The crop is grown both under irrigation and under natural rainfall conditions. In the humid areas of the country, the Middle Ganges region, the crop is grown only on the well-drained lands. Waterlogged soils cause root rot.

The production of corn in Africa is of economic importance in Egypt and in the Union of South Africa. The Egyptian crop is grown under irrigation. The entire crop is consumed locally. The acreage suitable for corn production in South Africa is limited by a deficiency of rainfall, but it is an important crop. According to Taylor (25) "corn production is centered chiefly on the high plateau in those areas in which rainfall is 25 to 40 inches per year,

most of it falling during the summer months, October to April. In the drier areas Kafir is more important." The principal commercial area of production lies north of Basutoland. The crop is grown by natives for home consumption over wide areas of the continent. The Union of South Africa exports around 20 million bushels of corn annually. The amount available for export from year to year is subject to a considerable fluctuation. This reflects on the unreliability of the crop in many of the areas of production.

Distribution in the United States. The distribution of corn in the United States is shown graphically in Fig. 77. Table 37 gives the statistical data for the most important states. While only ten of the highest corn producing states for the ten-year period 1928–1937 are listed in Table 37, it is evident from Fig. 77 that corn is an important crop in all of the vast areas from the Atlantic coast to the high plains. Nevertheless, there is a definite concentration of acreage in the Corn Belt. This is so outstanding that a defining of the limits of the Corn Belt is not necessary. It has already been indicated that the intensive production of corn in the heavily shaded portion of the map is occasioned by a combination of favorable climatic and soil conditions; in addition to this the

TABLE 37. CORN: ACREAGE HARVESTED, PRODUCTION, AND PERCENTAGE OF UNITED STATES TOTAL PRODUCTION IN SPECIFIED STATES RANKED ACCORDING TO PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGES AND PRODUCTION EXPRESSED IN MILLIONS.

Rank	States	Acreage Harvested	Production		
			Average 1928–1937, in Bu.	Percentage of U. S. Total, 1928–1937	1938, in Bu.
1	Iowa	10.98	393.14	17.02	479.18
2	Illinois	9.02	307.59	13.32	385.43
3	Nebraska	8.98	159.18	6.89	107.74
4	Indiana	4.49	151.20	6.55	173.39
5	Minnesota	4.65	136.35	5.90	157.54
6	Ohio	3.61	132.30	5.73	156.99
7	Missouri	5.54	113.66	4.92	109.00
8	Kansas	5.47	80.74	3.50	45.20
9	Texas	4.87	75.96	3.29	75.65
10	Wisconsin	2.24	71.04	3.07	90.51
	All others	39.95	688.51	29.81	781.57
	Total U. S.	99.80	2,309.67	100.00	2,562.20

topography of the land is adapted to the use of modern machinery. According to Baker and Genung, production in the Corn Belt exceeds 3,000 bushels per square mile and in some counties rises to 5,000 bushels. The factors accounting for the diminishing of the importance of the corn enterprise in all directions from the Corn Belt have been pointed out in previous discussions and need therefore not be restated here.

Sweet corn is grown in many sections of the United States; 430,000 acres were grown in 1937. The high producing states are Illinois, Minnesota, Iowa, Indiana, and Maryland.

Pop corn is also grown in many sections of the United States. Most of the commercial crop is produced in western Iowa, in Sac and Ida counties, and in east-central Nebraska, in Valley county. Iowa produces around 26,000 and Nebraska around 9,000 acres. These producing areas are shown in Fig. 82.

THE SORGHUMS

Commercial Importance. The sorghums are generally grouped into four classes in accordance with the characteristics of the plants and seeds and with regard to the uses made of them.

a. The grain sorghums are grown primarily for grain which may be used either for feed or food.

b. The sweet sorghums, or sorgos, are grown for forage and for the manufacture of sirup.

c. The grass sorghums, of which sudan grass is the most important, are grown for the production of hay and pasturage.

d. Broomcorn is grown primarily for the "brush" used in the manufacture of brooms.

The grain sorghums constitute the most important of the groups. In the United States they are used almost exclusively for the production of feed for livestock, though they have a limited use in the making of flour for pancakes and in the preparation of breakfast foods. In certain sections of the Old World, on the other hand, they have for centuries occupied the place of a staple food crop. As stated by Reed (20) "the inhabitants of Bombay and Madras Presidencies of India, of northern China, Manchuria and Chosen, of western Asia (including Syria, Turkestan and Mesopotamia), and of parts of Africa have depended largely upon this cereal for human, as well as animal, sustenance."

The sorgos are grown for forage and the production of sorgo sirup. In recent years around 15,000,000 gallons of sorgo sirup has been made annually in the United States.

Historical. According to Ball (1) "there can be no doubt of the great antiquity of the sorghum plant in cultivation. The story of its domestication is lost in the shadows of the past." The earliest known records of its culture come from Egypt. The crop is supposed to have been carried to Egypt by caravans from India where the crop has been cultivated since a remote period. The sorghums are also native to Africa; many of the types now being grown in the United States have been introduced from there.

The introduction of the sorghums into the United States is comparatively recent. The first recorded introduction was from China in 1853, by way of France. The Early Amber variety is reported to have come from this "Chinese sorgo." Seeds of 16 varieties of sorghum from Natal reached the United States in 1857; among them were Orange, Sumac, and Gooseneck. The first interest in the crop was from the standpoint of possible sugar production. In this the sugar beet, which offered a better source of crystallized sugar than the sorgos, won out. However, sorgo was found to be of value in making sirup. The introduction of the grain sorghums is more recent than that of the sorgos. Brown and White durra were introduced in 1876, White and Red Kafir in 1876, Milo in 1885. The kafirs and milos did not get into general cultivation until 1890 (Ball, 2). The sorghums became of real importance in the agriculture of the southern Great Plains area during the dry years in the early eighties, and again during the general drought of 1892–1894. Likewise the recent drought in the Great Plains area created greater interest in the sorghums not only in the southern, but also in the central and northern areas of this agricultural belt. The introduction of the sorghums has had a profound effect in stabilizing the agriculture of the Great Plains area. Sudan grass was not introduced into the United States until 1909. Vinall in speaking of sudan grass (27) states that "no other plant introduction ever gained such immediate and widespread popularity in the United States."

Climatic Relationships. The main outstanding feature of the sorghums is their ability to grow under dry conditions. In addition they are able to withstand high temperatures. As a matter of fact,

they are the only field crop approaching the true xerophytes. The comparative drought resistance of corn and the sorghums was discussed in detail in Chapter XV.

Not all varieties of sorghum are equally drought-resistant. In general the dwarf types will produce profitable crops under drier

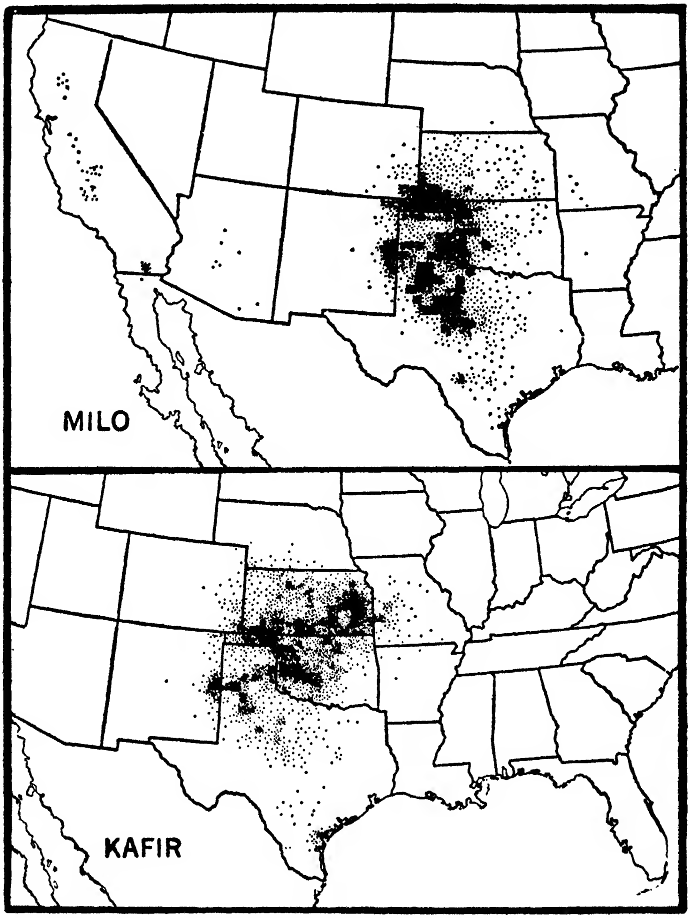


FIG. 80. Comparative distribution of Dwarf Yellow milo and Blackhull kafir (Standard and Dwarf) in the United States. Each dot represents 500 acres. Estimated acreages 1,526,000 for the milo and 1,801,400 acres for the kafir. (After Vinall, Stephens, and Martin.)

conditions than the tall-growing and leafier types. The physiological reasons for this have been discussed in previous chapters. Figure 80, compiled from Vinall *et al.* (28), shows the distribution

of Blackhull kafir (Standard and Dwarf) and Dwarf Yellow milo in the grain sorghum producing area of the United States. It is evident that the heavy concentration of Dwarf Yellow milo occurs under drier conditions than that of the kafir. In addition it should be noted that the tall kafir (the standard type) is grown in the eastern more humid and the dwarf type more largely in the western and drier area of distribution of the Blackhull kafir. Likewise standard broomcorn is produced under more humid conditions than the dwarf broomcorn.

Dry, sunny weather at harvest time favors the curing of the brush of broomcorn so that it will retain its natural green color. Excessive rain at harvest is detrimental to color and quality, the brush becoming weather-stained or red.

The sorgos generally require more humid conditions than the dwarf types of grain sorghums. This is the case especially when they are being grown for the manufacture of sirup. It is difficult to produce a high quality sirup under conditions of drought. Unless the climatic conditions are such as to ensure an uninterrupted development of the plants the impurities of the juice extracted from the stems will be too high to produce a good quality of sirup. This accounts for the growing of sorgos intended for sirup making in the humid areas of the Sorghum Belt.

Sudan grass can be grown under lower temperature conditions than the other sorghums; nevertheless, for best development the summer temperature must be fairly high.

Soil Conditions. The sorghums are grown over a great range of soil conditions. They respond to an abundance of organic matter and a liberal supply of plant nutrients. Since the sorghums can be grown on fairly light soils not well adapted to the growing of wheat, their cultivation is locally of importance on light-textured soils while the heavy-textured soils of the Sorghum Belt are used more extensively for wheat production. The sorghums do well on heavy soils, even on soils with a claypan; good aeration is, however, essential to proper growth.

The highest yields of both the grain and the sweet sorghums are produced on fertile soils well supplied with moisture. Likewise the highest yield and quality of brush are produced from broomcorn grown on fertile, well-watered soils. On fertile soils and especially in areas where moisture is fairly abundant the grain

sorghums as well as the sorgos come into direct competition with corn. Producers generally prefer to handle corn if conditions favor its production. On the other hand, the sorghums are the more reliable crop; on account of their greater drought resistance their yields fluctuate less from season to season under the erratic climatic conditions so common in the Sorghum Belt.

World Distribution. Reliable statistics on world sorghum production are not available. The crop is extensively grown in northern China and Manchuria, in India, and is widely distributed in Africa.

Northern China and Manchuria specialize in the production of a hardy group of sorghums known as "kaoliang." This group of sorghums can be grown under lower temperatures than other grain producing types; it is also very drought-resistant. The light-colored varieties are principally used for grinding into flour and making cakes, while the dark-colored types are used mainly for feed. The grain of kaoliang is also used for distilling the potent spirit called "Shamshu" so common in North China. The coarse stalks are used for fuel, for the making of baskets and mats, and even in the construction of shelter. The sorghums assume a place of importance mostly in areas too dry for the production of corn.

The sorghums are very important in India. Reed reports that approximately 25 million acres are produced annually. The sorghums together with the millets are of special importance in the drier areas of the country. According to Reed, two distinct types of sorghum crops are grown: "the summer crop, or Kharif jowar, sown in the spring and harvested in the fall, and the *Rabi* crop, or winter jowar, sown in September or October and harvested in the following February or March." Throughout India, the grain of the sorghums is used largely for human consumption. The sorghums are generally grown on the more fertile, the millets on less fertile and drier soils.

The sorghums make up the staple cereal for a large proportion of the native population of Africa. The crop is widely distributed over Africa. Some of the important varieties used in the United States originated in this continent; others were introduced from India.

Europe does not produce any appreciable amount of grain sorghum. Broomcorn is, however, of local importance in parts of Italy and Hungary.

Distribution in the United States. Figure 81, taken from Martin and Stephens (14), gives an outline map showing the distribution of the grain sorghums and sorgos in the United States. These authors also give the varietal regions of the country. Table 38 gives the statistical data of the high-producing states of grain sorghums. It will be observed that the grain sorghum acreage is centered in the southern Great Plains area. This is accounted for by the drought resistance of the crop. It is evident that the eastern extension of the Grain Sorghum Belt and the western limits of intense corn production are somewhat complementary.

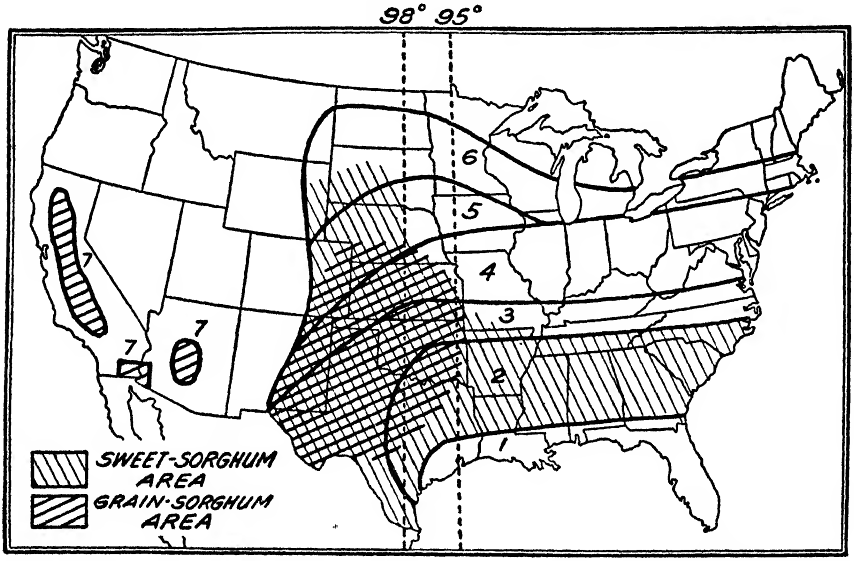


Fig. 81. The sweet and grain sorghum producing areas of the United States (After Martin and Stephens.)

This offers another good example of the introduction of a new crop to lend stability to agricultural production. The introduction and rapid utilization of the grain sorghums with their greater tolerance to drought and less specific demands of the environment during pollination as compared with corn have been of great help in the establishment of a sound agriculture in the southern Great Plains. During recent years the production of the grain sorghums has become of increasing importance in the irrigated sections of southern Arizona and also in California. The recent drought in the Great Plains area has created a great interest in the sorghums

in the central and even northern portions of this region. Note the high acreages of grain sorghums in Nebraska, South Dakota, and Colorado in 1938.

TABLE 38. GRAIN SORGHUMS: ACREAGE HARVESTED, PRODUCTION, AND PERCENTAGE OF UNITED STATES TOTAL PRODUCTION IN SPECIFIED STATES RANKED ACCORDING TO PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGES AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	*States*	*Acreage Harvested*	*Production*		
			Average 1928–1937, in Bu.	Percentage of U. S. Total 1928–1937	1938, in Bu.
1	Texas	3,561	47,741	55.32	46,951
2	Oklahoma	1,441	12,932	14.98	12,716
3	Kansas	1,268	12,886	14.93	14,773
4	New Mexico	305	3,484	4.04	2,975
5	California	104	2,999	3.47	4,495
6	Missouri	188	2,085	2.42	3,625
7	Colorado	227	1,816	2.10	4,631
8	Arizona	35	947	1.10	1,102
9	Nebraska	92	752	0.87	4,890
10	Arkansas	70*	662*	0.77	570
11	South Dakota . . .	—	—	—	2,408
	Total U. S.	7,291	86,304	100.00	99,136

*Short-time average.

The sorgos are of greatest importance in the same area devoted to the intensive production of the grain sorghums; the area of distribution is, however, not so concentrated. In other words, the sorgos are grown to a greater extent in the humid area of the country than the grain sorghums. This is brought out in Fig. 81. In humid areas corn is in a better competitive position than the grain sorghums in the production of concentrates. In the western area the sorgos are produced almost exclusively for forage, while their production for purposes of making sirup is of considerable importance in the eastern more humid area. The reason for this was discussed under the heading of climatic relationships. The sorgos are used extensively as a silage crop in the central area of their distribution.

The intense broomcorn producing areas of the United States are indicated in Fig. 82. Martin and Washburn (13) recognize three

important production districts or centers. The oldest of these is located in east-central Illinois, with Mattoon as the chief marketing point. The second is in south-central Oklahoma, with Lindsay as the marketing point. These two districts produce a high quality of standard broomcorn. The third or dwarf broomcorn producing district comprises western Oklahoma, southwestern Kansas, southeastern Colorado, and eastern New Mexico. Broomcorn is also grown locally in other central and southern portions of the United States. The important commercial areas of production are, however, well concentrated in the above three districts.

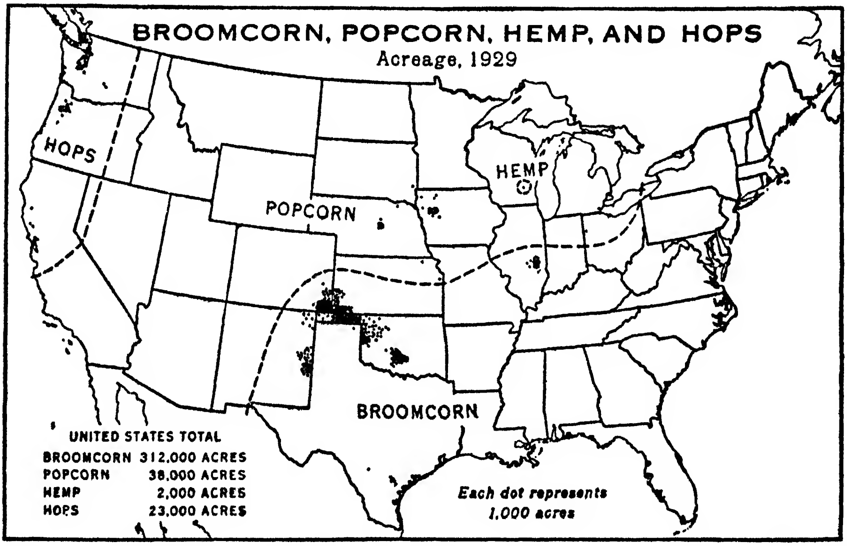


Fig. 82. Distribution of broomcorn, popcorn, hemp, and hops in the United States in 1929. Each dot represents 1,000 acres (After Baker and Genung.)

MILLETS

Commercial Importance. Like the sorghums, millets are grown for feed in the United States but constitute an important cereal for human consumption in parts of Asia and Africa and practically in the same areas where the sorghums are produced for that purpose. Millet is used to some extent in the Balkan States and Russia in the manufacture of alcohol and fermented alcoholic drinks.

Four major types of millet are grown: foxtail (*Setaria italica*), proso (*Panicum miliaceum*), barnyard or Japan millet (*Echinochloa*

frumentacea), and pearl millet (*Pennisetum glaucum*). The first two are of greatest importance in the United States. Foxtail millet is grown for forage, while proso is produced as a grain crop. The popularity of millets for the production of forage has decreased materially since the introduction of sudan grass which under most conditions produces not only a greater quantity but also a better quality of hay. The proso, also called broomcorn and hog millet, is used as a short-season crop and in instances can be used to advantage as a catch crop.

Historical. The cultivation of the millets dates back to ancient times. They were grown by the lake-dwellers of Switzerland during the Stone Age. According to Bretschneider, the millets were mentioned in connection with religious ceremonies in Chinese records about 2700 B.C. The millets are native to southern Asia. Extreme susceptibility to frosts bespeaks their southern origin. According to Vinall (26), a distribution of millet was made by the United States Patent Office in 1849; by 1889 the crop was of considerable importance. The now commercially important varieties of proso millet were not introduced until toward the end of the past and the beginning of the present century.

Climatic Relationships. All the millets are high temperature loving plants, but on account of the ability of early varieties to mature in a short period of time, from 60 to 90 days from sowing to maturity, they can be grown in northern areas where summer temperatures are high. The millets are very efficient in the use of water. The young plants demand a fair amount of moisture, but after they are once established they are fairly drought-resistant. The rather limited root system of proso millet accounts for its lack of resistance to severe drought.

World Distribution. The millets are of importance in China, India, Africa, in the Balkan States, and in southern Russia. In China and India they are grown in the same general areas as the sorghums. The millets often occupy the poorer and the sorghums the better lands. The production of millet in Africa is largely limited to the northern portion of that continent (Schindler, 21). The most important producing section in Europe is found in southern Russia; the crop is of less importance in the Balkan States, of somewhat greater importance on the level lands of the Hungarian plains, and then decreases to a place of but limited importance in

southern Germany. Proso millet is grown to some extent in Asiatic Russia.

Distribution in the United States. The forage producing millets are of but limited importance in the United States, where they have been largely replaced by sudan grass. Some millet hay is, however, still produced from Kentucky and Tennessee to the Great Plains area. Proso millet is used as a catch crop in the central and northern Great Plains region. It is also grown in the prairie provinces of Canada. Under favorable conditions a grain crop can be produced from this millet in cases where the main crop has failed. Generally the millets and especially the proso millet are not sufficiently productive to replace any main crop grown in an area.

REFERENCES

1. Ball, C. R., "The history and distribution of sorghum," *U. S. Dept. Agr. Bur. of Plant Ind. Bull.* 175, 1910.
2. ———, "The importance and improvement of the grain sorghums," *U. S. Dept. Agr. Bur. of Plant Ind. Bull.* 203, 1911.
3. Baker, O. E., "A graphic summary of American agriculture based largely on the census," *U. S. Dept. Agr. Misc. Pub.* 105, 1931.
4. ———, and A. B. Genung, "A graphic summary of farm crops," *U. S. Dept. Agr. Misc. Pub.* 267, 1938.
5. Becker, A., "Herkunft, Anbau und Nährstoffansprüche des Maises unter besonderer Berücksichtigung des deutschen Körnermaises," *Die Ernährung der Pflanze*, 34:59–65 (1938).
6. Bergsmark, D. R., *Economic Geography of Asia.* Prentice-Hall, New York, 1936.
7. Burtt-Davy, J., *Maize: Its History, Cultivation, Handling, and Uses.* Longmans, London, 1914.
8. Finch, V. C., and O. E. Baker, *Geography of the world's agriculture.* Govt. Printing Office, Washington, 1917.
9. Hughes, H. D., and E. R. Henson, *Crop Production.* Macmillan, New York, 1930.
10. Jacobs, P. B., and H. P. Newton, "Motor fuel from farm products," *U. S. Dept. Agr. Misc. Pub.* 327, 1938.
11. Jenkins, M. T., "Corn improvement," *U. S. Dept. Agr. Yearbook* 1936: 455–522.
12. Leighty, C. E., C. W. Warburton, O. C. Stine, and O. E. Baker, "The corn crop," *U. S. Dept. Agr. Yearbook* 1921:161–226.

13. Martin, J. H., and R. S. Washburn, "Broomcorn growing and handling," *U. S. Dept. Agr. Farmers Bull.* 1631, 1930.
14. ———, and J. C. Stephens, "The culture and use of sorghums for forage," *U. S. Dept. Agr. Farmers Bull.* 1844, 1940.
15. Mangelsdorf, P. C., and R. G. Reeves, "The origin of Indian corn and its relatives," *Tex. Agr. Exp. Sta. Bull.* 574 (Monograph), 1939.
16. Michael, L. G., "Agricultural survey of Europe," Pt. 1, The Danube Basin, *U. S. Dept. Agr. Bull.* 1234, 1924.
17. ———, "Agricultural survey of Europe," Pt. 2, The Danube Basin, Rumania, Bulgaria, and Yugoslavia, *U. S. Dept. Agr. Tech. Bull.* 126, 1929.
18. ———, "Agricultural survey of Europe," Hungary, *U. S. Dept. Agr. Tech. Bull.* 160, 1930.
19. Morgan, M. F., J. H. Gourley, and J. K. Ableiter, "The soil requirements of economic plants," *U. S. Dept. Agr. Yearbook* 1938:753–776.
20. Reed, G. M., "Sorghums," *Brooklyn Bot. Garden Leaflets*, Series XIII: 1–12, 1925.
21. Schindler, F., *Handbuch des Getreidebaus.* Paul Parey, Berlin, 1923.
22. Shepherd, G., J. J. Dalton, and J. H. Buchanan, "The agricultural and industrial demand for corn," *Iowa Agr. Exp. Sta. Bull.* 335, 1935.
23. Spafford, W. J., "Agriculture in the temperate and sub-tropical climates of the South," *Dept. Agr. of So. Australia, Bull.* 310, 1936.
24. Taylor, A. E., *Corn and Hog Surplus of the Corn Belt.* Food Res. Inst., Stanford University, 1932.
25. Taylor, C. C., "Agriculture in Southern Africa," *U. S. Dept. Agr. Tech. Bull.* 466, 1935.
26. Vinall, H. N., "Foxtail millet; its culture and utilization in the United States," *U. S. Dept. Agr. Farmers Bull.* 793, 1917.
27. ———, "Sudan grass," *U. S. Dept. Agr. Farmers Bull.* 1126, 1935.
28. ———, J. C. Stephens, and J. H. Martin, "Identification, history and distribution of common sorghum varieties," *U. S. Dept. Agr. Tech. Bull.* 506, 1936.
29. Wallace, H. A., and E. N. Bressman, *Corn and Corn Growing.* Wallace Pub. Co., Des Moines, 1923.

Chapter XXIV

EDIBLE LEGUMES

INTRODUCTION

Certain of the larger seeded legumes occupy an important place in human nutrition. They are prized not only for their high energy values but especially for the highly important protein that they supply to the diet. The edible legumes are particularly important in regions where population pressure, economic stress, or environmental conditions limit the production of livestock and the utilization of animal products to provide the necessary protein. The cereals do not supply a sufficient amount of protein for the diet; consequently, the seeds of legumes are utilized to provide the required protein. Under such conditions the seeds of the edible legumes may be designated as the poor man's meat. Thus the pulses are of great importance in the diets of the masses of Brazil, the Mediterranean countries, in the Balkans, and especially in the Far East. All of these areas make but limited use of the more expensive animal products.

In addition, it is well to keep in mind that a relatively high percentage of the protein supplied by legumes is traceable to the fixation of atmospheric nitrogen with the aid of symbiotic bacteria. The relationship of this to soil fertility is evident.

BEANS

Types of Beans. When the term "bean" is used most readers will think of the common field or garden bean, *Phaseolus vulgaris.* This is the most important species covered under the broad term. Nevertheless, it represents but one of the 17 species of beans listed by Thompson (8). The 17 species represent six genera: (1) broad bean or Windsor bean (*Vicia faba*), (2) kidney or common field or garden bean (*Phaseolus vulgaris*), (3) Metcalfe bean (*P. metcalfei*), (4) tepary bean (*P. acutifolius*), (5) scarlet runner or multiflora

bean (*P. coccineus*, also called *P. multiflorus*), (6) small lima or sieva bean (*P. lunatus*), (7) large lima bean (*P. limensis*), (8) urd bean (*P. mungo*), (9) mung bean (*P. aureus*), (10) adzuki bean (*P. angularis*), (11) rice bean (*P. calcaratus*), (12) moth bean (*P. aconitifolius*), (13) asparagus bean or yard-long bean (*Vigna sesquipedalis*), (14) cowpea (*Vigna sinensis*), (15) hyacinth bean (*Dolichoes lablab*), (16) velvet bean (*Stizolobium Deeringianum*), and (17) soybean (*Glycine max* or *Soja max*).

Not all of these species are of importance in human nutrition; many of them are used only under special conditions. Thus the broad or Windsor bean is grown in the United States only in California. It is, however, of some importance in Europe and especially in the Mediterranean area. The other beans besides the kidney or common field bean used to any great extent for human food in the form of the dry seed are the large seeded lima, the sieva or small seeded lima, the tepary, and the soybean. The soybean is used for human consumption to but a limited extent in the United States; it constitutes a very important article of food in China, India, and Japan. The cowpea (blackeye bean) constitutes a staple food product especially in the southern states.

Historical. According to Hardenburg (2), "historical records contain numerous references to the early cultivation and uses of beans of various types. These are in many cases not sufficiently detailed to indicate either the genus or species referred to. Literature records the cultivation of beans, lupines, and lentils in the Nile Valley as early as 2000 B.C."

Climatic Requirements. Beans are warm-season annuals, sensitive to extremes of temperature and requiring a relatively high humidity. The optimal seasonal temperature for beans is about the same as that for corn. The plants are extremely susceptible to frost injury. For this reason proper air drainage is essential where the crop is grown in northern areas. The length of the growing season is generally not a factor in distribution. Most varieties of pea beans mature in from 100 to 110 days, while the latest varieties of the kidney type seldom require more than 125 days from planting to maturity.

Beans demand a fairly uniform supply of moisture during their vegetative period. Abnormally high rainfall is detrimental to the crop; likewise overirrigation must be avoided. Since the crop

is readily damaged by weathering, dry conditions at harvest time are essential to the production of bright, high-quality seed.

Certain varieties of common field beans (*P. vulgaris*) such as the Pinto, Pink, and Red Mexican are, according to Hardenburg, probably more heat- and drought-resistant than ordinary varieties. This accounts for their production in dry land areas in Colorado and New Mexico. But even these varieties of common beans are not so well adapted to semiarid conditions as the tepary bean (*P. acutifolius*). Hendry (4) also comments on the ability of the tepary bean to survive "in the hot, dry climate of the interior valley uplands" of California, that is, under conditions too severe for varieties of common, and lima, beans.

Soil Relationships. Beans are grown on a relatively wide variety of soils. While the crop responds to an available supply of plant nutrients and organic matter, soil fertility is usually less likely to constitute a limiting factor in bean production than in most other field crops. Soil aeration and temperature are important factors especially in relation to obtaining good stands. Neither heavy mineral soils nor soils of organic origin are well suited for bean production. Clay soils are too much subject to puddling, while peat or muck soils are likely to produce not only a late-maturing crop but also one with an undue proportion of vine to seed. The best yields are obtained on medium loams of moderate fertility. Even relatively light soils can be used for bean production under favorable moisture conditions.

World Distribution. Table 39 gives the statistics of world production of dry edible beans. The United States does not under normal conditions produce enough beans to supply the domestic demand. The largest part of the Brazilian crop is consumed locally. The most important surplus producing region in the world is the Danube Valley, including Rumania, Bulgaria, and other Balkan countries. Japan also exports a high percentage of its crop of white beans.

Table 39 brings out the fact that beans are an important food crop among southern European and southern Asiatic peoples. No statistical data are available on bean production in India; it is known, however, that the crop is of considerable importance in that country. The Garbanzo bean or the so-called chick pea (*Cicer arietum*) is an important article of food of the peoples of India

as well as those of northern Africa, Spain, and of all South and Central American countries.

TABLE 39. WORLD PRODUCTION OF DRY EDIBLE BEANS IN SPECIFIED COUNTRIES FOR THE PERIOD 1930–31 TO 1934–35

Rank	*Country*	*Average Production, in Bags of 100 Lbs.*	*Production, in Percentage of World Total**
1	Brazil	15,855,000	22.61
2	United States	12,443,000	17.74
3	Egypt	7,066,000	10.07
4	Rumania	6,280,000	8.95
5	Italy	3,548,000	5.06
6	Spain	3,468,000	4.94
7	Yugoslavia	2,980,000	4.25
8	Mexico	2,910,000	4.15
9	France	2,806,000	4.00
10	Great Britain	2,804,000	4.00
11	Japan **	1,933,000	2.76
12	Chile	1,746,000	2.49
13	Bulgaria	1,532,000	2.18
14	Hungary	1,448,000	2.06
	All others	3,319,000	4.73
	Estimated world total excluding U.S.S.R. and India	70,138,000	100.00

* Production in Russia and India is not considered in calculation.

** Production in Hakkaido Province, where most of the dry edible bean varieties are grown.

In the United States the soybean is not classified as a "dry edible bean," and the crop does not appear in statistical data as such. It is grown primarily as a forage and oil-producing crop. However, in recent years a considerable interest has been shown in the use of soybeans for human consumption in this country. It is a food crop of great importance in China and Japan. The most important soybean producing countries of the world in order of their importance are China, Manchuria, the United States, Chosen, Japan, and Netherland India. A great variety of food products ranging from vegetable milk to cheese are produced from soybean seeds.

Distribution in the United States. Field beans are produced over a wide range of conditions in the United States. Intensive humid producing areas are found in Michigan and western New York. The crop in northern Idaho is grown under subhumid

conditions. The extensive areas devoted to beans in Colorado and New Mexico are in dry-farming regions, while the crops of southern Idaho, Montana, and Wyoming are grown under irrigation and the California crop is grown under a variety of conditions.

Table 40 gives the statistics of bean production by states. Figure 83 shows the distribution of the crop cartographically.

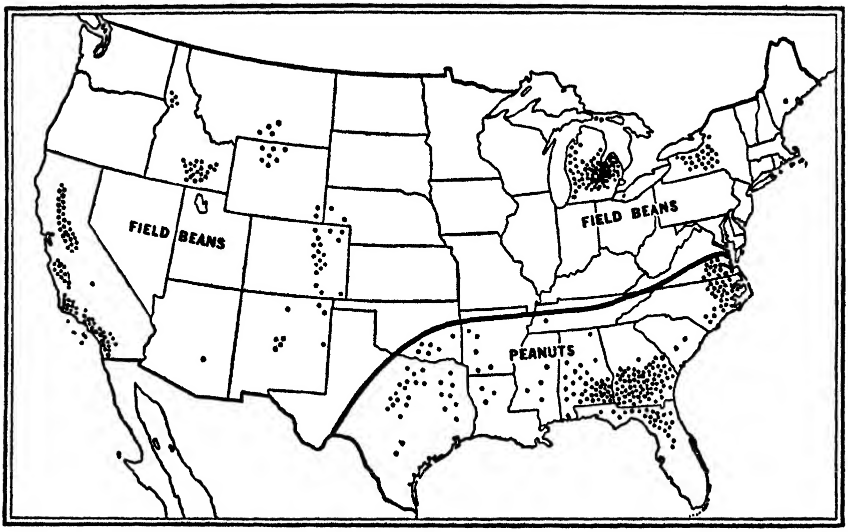


FIG. 83. Distribution of dry edible beans and peanuts in the United States, average for the years 1934–1938 for beans and for the years 1928–1937 for peanuts. Each dot represents 50,000 bags of beans and 10,000 acres of peanuts.

Young (10) presents data dealing with the intensity of bean production in each of the important bean growing states of the Union.

Michigan continues to be the most important bean producing state from the standpoint of acreage devoted to the crop. The total production is slightly higher in California than in Michigan. The crop is well distributed throughout the south-central and eastern parts of Michigan, the greatest intensity of production being found near Saginaw Bay. Some counties devote as high as 20 per cent of their total harvested crop area to beans. Michigan produces approximately 90 per cent of the pea beans of the United States. Conditions in this humid area are quite similar to those prevailing in the western New York area. Production is not, however, so intensive in New York as in Michigan.

TABLE 40. BEANS: ACREAGE HARVESTED AND PRODUCTION OF DRY EDIBLE BEANS IN THE MAIN PRODUCING STATES — AVERAGES FOR THE FIVE-YEAR PERIOD 1934–1938

Rank	States	Acreage Harvested		Production	
		In 1,000 Acres	Percentage of U. S. Total	In 1,000 Bags of 100 Lbs. Each, Cleaned Basis	Percentage of U. S. Total
1	California	344	20.81	4,052	32.0
2	Michigan	517	31.28	3,940	31.2
3	Idaho	110	6.65	1,327	10.5
4	New York	152	9.20	1,104	8.7
5	Colorado	287	17.36	893	7.1
6	Wyoming	—	—	434	3.4
7	New Mexico	—	—	404	3.2
8	Montana	—	—	197	1.6
9	Nebraska	—	—	123	1.0
10	Maine	—	—	67	0.5
	All others	243	14.70	105	0.8
	Total U. S.	1,653	100.00	12,646	100.0

Because of distinct climatic variations, the state of California produces a large number of types of beans. The interior valleys grow the Pink, Blackeye, Red Mexican, and White Tepary varieties. Small Whites are grown in the more favored districts. California is especially important from the standpoint of lima bean production. This crop is very specific in its environmental demands; as a result the area of production is quite restricted. Virtually the entire crop of lima beans is limited to portions of five counties on the coast of southern California. The warm, humid climate of the southern coastal region is especially adapted to the growth of this important type of bean.

Idaho has two bean producing areas. The most important one, the Twin Falls area in the southern part of the state, is irrigated. A high percentage of the acreage is of the Great Northern and Red Mexican types. Idaho produces around 58 per cent of the Great Northern beans of the United States. The crop in the northern districts, Lewiston-Troy area, is grown without irrigation. The Small White Flat type is the most important variety.

The rather limited areas of Montana and Wyoming are given over largely to the production of the Great Northern variety.

Dry conditions cause low and variable yields of the bean crops of Colorado and New Mexico. Some of the east-central Colorado counties have in excess of 25 per cent of their harvested crop area in beans. The production of the crop in central New Mexico is also very intensive from the standpoint of relative acreage devoted to beans. Some counties have as high as 30 per cent of their harvested crop land in beans. In 1924 Torrance county devoted 75.3 per cent of its harvested crop area to this plant. Owing to dry conditions, Pinto is the most commonly grown variety in Colorado and New Mexico.

The production trend of dry beans in the United States has been definitely upward since the early 1920's. Pond (6) brings out that the "production of dry edible beans in the United States declined from over 10,000,000 bags of 100 pounds each in 1918 to 6,042,000 bags in 1920, but has since increased on the average, until in the 1937 season the record crop of 15,839,000 bags was produced. Production averaged 11,927,000 bags during the 5-year period, 1927–31, and 12,179,000 bags in the 5 years, 1932–36." Table 40 gives the average production for the period 1934–1938.

PEAS

Utilization. Peas are used for canning, as green market or home garden peas, as dry peas, and recently for freezing. The crop is also used to a limited extent for forage. The vines of peas used in canning and for the preparation of frozen peas have value as feed for livestock.

The production of seed peas for planting the acreages of the crop for the various purposes indicated above constitutes an important enterprise. Each of these enterprises demands varieties with special characteristics as to growth habit and quality.

Peas are used not only as a vegetable but also in the form of dry peas. The dry peas are used either as whole or split peas and largely in the preparation of soup. In years when the crop of canning peas is short, dry peas may upon soaking be utilized for canning.

Damaged dry peas, or peas of low quality, can be utilized to advantage in livestock feeding, providing a feed high in protein.

Historical. Peas probably originated in Ethiopia, in Mediterranean Europe, and in southwestern Asia. Their origin is known

to be remote. Peas were first used almost exclusively in the form of the dry, cooked seeds. The extensive utilization of the crop in the canned and green state is comparatively recent. The increase in the use of peas in these forms corresponded with the development of methods of processing the green seeds and in improvements of transportation facilities. The development of the "viner," a machine capable of removing the peas from the vines and pods, greatly facilitated the handling of the crop for canning purposes.

The early writer distinguished between garden (*Pisum sativum*) and field peas (*P. arvense*). Since, however, these two types are completely cross-fertile, the distinction is entirely artificial, and both are now considered under *P. sativum*. Varieties with colored flowers were formerly considered as field while those with white flowers were regarded as garden peas. At the present time the colored-flowered varieties of edible peas have practically disappeared. About the only extensively grown variety of peas with colored flowers at the present time is the Austrian Winter pea, and it is used exclusively for green manure and forage purposes in the southern states.

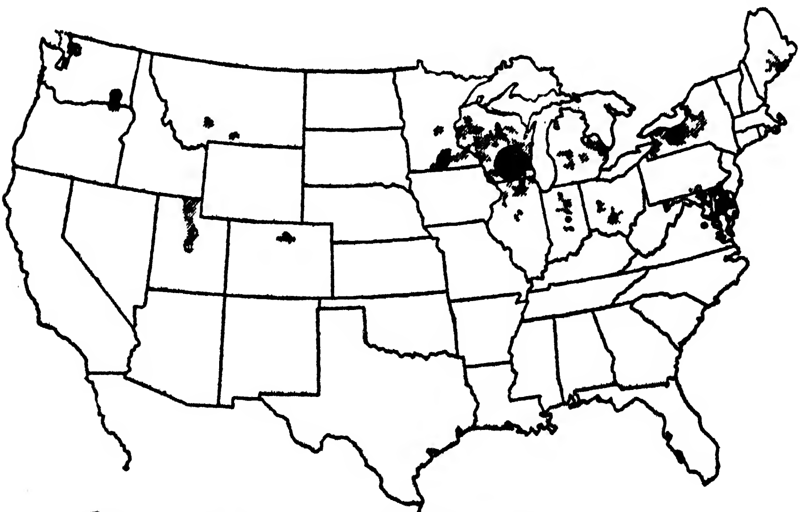
Climatic Relationships. Peas thrive best in cool, relatively humid climates. When grown in the south they must be planted early so that they may take advantage of the cooler months. Even in northern areas the highest yield and best quality of crop is obtained from early seedings. In contrast to beans peas are able to withstand relatively low temperatures, especially during the seedling stage. Hot, dry weather interferes with the setting of seed and lowers the quality of the seed produced. Bright, dry weather is desirable as the crop approaches maturity and during harvest.

Soil Relationships. Peas do best on soils of a moderately high level of fertility. Very high soil fertility leads to excessive vine production and lodging of the crop. The main essential of soils suitable for the production of peas is that they be well drained. For best returns the texture and structure of the soil should be such as to allow for relatively large amounts of readily available moisture for the use of the plants. The soil reaction should fall between slightly acid and slightly alkaline. When peas are used for the production of hay they are usually sown in combination with a cereal such as oats. The cereal serves to support the pea vines

and thus reduces the amount of lodging. Furthermore, a mixed pea and cereal hay cures more readily than straight pea hay.

World Distribution. Statistical data on the distribution of peas are fragmentary. Peas are an important crop in northern Europe and especially in England, the Scandinavian countries, Germany, the Netherlands, and France. The temperature in southern Europe and in the Mediterranean area is too high for the production of the field pea. In these areas lentils and the chick pea take the place of the field pea. According to Wade (9), Russia at the present time probably surpasses all other countries in the production of dry edible peas. The crop is reported to be of especial importance in the north-central part of the Soviet Union, east of Leningrad, west of Moscow, and in southwestern Siberia. The summer temperature of southern European Russia is too high for the successful production of peas.

Distribution in the United States. In discussing the distribution of peas in the United States it is necessary to point out the specific purposes for which the crop is grown, such as for manu-



General area in which canning peas are produced.

Section of the state in which the production of canning peas is most densely concentrated. The areas of the circles roughly indicate the relative size of the industry in the various states during the five-year period 1934–38.

FIG. 84. Distribution of canning peas in the United States. (After Rufener.)

facture, that is, either for canning or freezing, for direct marketing, production of peas for seed purposes, and production for dry peas.

Figure 84, taken from Rufener (7), shows the distribution of the canning pea producing areas. The important states, together with the 1939 pack in thousands of cases, are Wisconsin, 4,595; Oregon, 1,627; Washington, 1,576; New York, 1,385; Minnesota, 1,363; Utah, 1,046; and Illinois, 1,033.

Important producers of market garden peas are California, New York, Colorado, North Carolina, South Carolina, New Jersey, and Virginia. The total acreage devoted to this type of pea is small.

The important seed pea producing areas are found in Wisconsin, California, the Bitterroot and Gallatin Valleys of Montana, the Upper Snake River Valley of Idaho, and the Palouse region of northern Idaho and eastern Washington.

Dry peas are produced in the Palouse region, in Colorado, Wisconsin, Michigan, and Montana. The Palouse region of northern Idaho and eastern Washington produces around 50 per cent of the dry edible pea crop of the United States. Alaska and First and Best are the two most important green- and yellow-seeded varieties employed in the production of dry edible peas.

LENTILS

The lentil (*Lens esculenta*) is a small vetch-like plant highly prized for its lens-shaped, nutritious seeds, used chiefly for soups and stews. The lentil is used extensively by the peoples of the Mediterranean area, and to a lesser degree in western and central Europe. The seeds are either gray or red; different varieties also differ materially in the size of the seed. The large-seeded types are especially in demand in the United States. The main outlet for lentils in this country is found among the foreign-born populations of our eastern industrial centers. The Jewish population and peoples of Latin extraction in these eastern centers are heavy consumers.

According to Hedrick *et al.* (3), "the lentil has been in cultivation from very remote times. Lentil seeds were found in the prehistoric dwellings on the Swiss lakes, in Germany at Schussenried, in Switzerland, in Italy and Hungary, and also in the ruins of Troy. It was cultivated to a large extent in Egypt and exported from there to Greece and Rome. According to Schweinfurth, the lentil

was originally introduced to Egypt from Mesopotamia." The lentil is probably a native of eastern Asia from Baluchistan and Afghanistan to southern and eastern Persia.

The lentil demands fairly high temperatures. It thrives in the climates of the Mediterranean area, where most of the crop is produced. Production in the United States is very limited. A small acreage is grown in eastern Washington. Chile produces lentils in quantities for export. In northern areas the crop is produced on warm, well-drained soils. Southern slopes are desirable.

PEANUTS

The peanut, or groundnut (*Arachis hypogaea*), is, properly speaking, a pea rather than a nut. The seeds of this plant have the flavor and many of the other characteristics of true nuts; they are therefore widely utilized for the same purposes as true nuts. Peanut oil is one of the world's important food oils. A ton of shelled peanuts produces from around 500 to 700 pounds of oil depending on the variety and quality of the crop. Peanut butter is another valuable and nutritious product. The peanut is also used extensively in the feeding of livestock. The tops of the plants may be used for hay. The seed is commonly fed to hogs with the hogs doing the harvesting.

The peanut is strictly a warm-season crop and is found for that reason only in tropical or subtropical climates. The crop demands a moderate amount of moisture throughout the growing season. Most of the crop is produced in areas with more than 40 inches of annual precipitation.

Soil conditions influence both the yield and quality of the crop produced. The highest yields are obtained on the heavier textured soils provided that these soils do not become too compact. The best quality of peanuts is produced on light soils. Even light sandy soils can be used under favorable moisture conditions. Heavy, dark-colored soils stain the hulls and lower the market value, especially of the large varieties commonly sold in the hull. Good soil drainage is essential.

The peanut originated in America; it is probably a native of Brazil. It has long been used by native tribes in South America. According to Hutcheson *et al.* (5),

"the peanut was brought to the United States during the early days of colonization, but it did not become commercially important until about 1870. The growth was gradual from that time to about 1900 when the cultivation received a rapid impetus due to the spread of the boll weevil in the South. In 1909 there were 870,000 acres of peanuts grown — an increase of 68 per cent over the production of 1900."

Table 41 gives the statistical data of peanut production in the United States. It will be observed that around 58 per cent of the crop is harvested for nuts. Figure 83 shows the distribution of the crop cartographically. Baker and Genung (1) point out that "peanuts for human consumption are grown mostly in the Virginia-North Carolina district between Richmond and Raleigh. Those grown in Georgia, Alabama, and Florida, in Texas and Oklahoma, are the smaller Spanish variety and are mostly fed to hogs or made into peanut butter or oil."

TABLE 41. PEANUTS: TOTAL ACREAGE, ACREAGE HARVESTED FOR NUTS, AND PRODUCTION OF NUTS — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937. ACREAGE AND PRODUCTION EXPRESSED IN THOUSANDS.

Rank	States	*Acreage*			*Production of Nuts*	
		Total	Harvested for Nuts	Percentage of U. S. Total	Average 1928–1937, in Lbs.	Percentage of U. S. Total
1	Georgia	798	455	33.63	290,346	29.36
2	Alabama	440	224	18.54	142,400	14.40
3	Florida	271	58	11.42	32,488	3.28
4	Texas	262	156	11.04	73,876	7.47
5	North Carolina	245	226	10.32	238,750	24.14
6	Virginia	144	143	6.07	148,630	15.03
7	Oklahoma	61	36	2.57	17,104	1.73
8	Arkansas	53	18	2.23	8,965	0.91
9	Mississippi	37	25	1.56	13,484	1.36
10	Louisiana	31	11	1.31	5,421	0.55
11	South Carolina	18	12	0.76	8,517	0.86
12	Tennessee	13	13	0.55	9,032	0.91
	Total U. S.	2,373	1,377	100.00	989,013	100.00

World statistics on the distribution of the peanut acreage are not available. Figures, however, are available on the international export trade in peanuts. These are presented in Table 42. While the data in Table 42 show the origin of peanuts entering into international trade, they do not give all the producing countries.

They do show that the crop is of special importance in the Orient and in Africa. The crop is also grown in Mediterranean Europe. The United States generally imports more peanuts than are exported. The peanut may be expected to become of greater importance in the southern and particularly in southeastern states with further developments of the livestock industries and especially of swine production in these states.

TABLE 42. INTERNATIONAL EXPORT TRADE IN PEANUTS, AVERAGES 1930–1934

Rank	*Principal Exporting Countries*	*Exports, in 1,000 Pounds*	*Percentage of World's Export Trade*
1	British India	1,290,773	32.79
2	Senegal	915,385	23.26
3	Nigeria	634,259	16.11
4	China	534,578	13.58
5	Manchuria*	179,149	4.55
6	Gambia	142,543	3.62
7	Mozambique	81,267	2.06
8	Portuguese Guinea	53,036	1.35
9	Netherland India	45,803	1.16
10	Tanganyika	42,665	1.08
	All others	16,502	0.44
	World total export trade	3,935,960	100.00

* Three-year average.

REFERENCES

1. Baker, O. E., and A. B. Genung, "A graphical summary of farm crops," *U. S. Dept. Agr. Misc. Pub.* 267, 1938.
2. Hardenburg, E. V., *Bean Culture.* Macmillan, New York, 1927.
3. Hedrick, U. P., F. H. Hall, L. R. Hawthorn, and A. Berger, *The Vegetables of New York,* Vol. 1 — Part 1, "Peas of New York." J. B. Lyon Company, Albany, 1928.
4. Hendry, G. W., "Bean culture in California," *Cal. Agr. Exp. Sta. Bull.* 294, 1921.
5. Hutcheson, T. B., T. K. Wolfe, and M. S. Kipps, *The Production of Field Crops.* McGraw-Hill, New York, 1936.
6. Pond, R. K., "Major economic trends in the dry edible bean industry," *U. S. Dept. Agr., Agr. Adj. Adm., Marketing Information Series,* GCM — 6, 1938.

7. Rufener, W. W., "Production and marketing of dry peas in the Palouse Area," *Wash. Agr. Exp. Sta. Bull.* 391, 1940.
8. Thompson, H. C., *Vegetable Crops.* McGraw-Hill, New York, 1931.
9. Wade, B. L., "Breeding and improvement of peas and beans," *U. S. Dept. Agr. Yearbook* 1937:251–282.
10. Young, H. N., "Production and marketing of field beans in New York," *New York Agr. Exp. Sta. Bull.*, 532, 1930.

Chapter XXV

POTATOES, SWEET POTATOES, YAMS, AND OTHER ROOT CROPS

THE WHITE POTATO

Importance as a Food Crop. The white potato (*Solanum tuberosum*) is one of the most efficient of starch producing plants. In cool regions and especially in relatively moist, cool areas with soils too light for the economical production of wheat, the potato has no rival as a producer of food. Rye is the only crop plant approaching its efficiency under the adverse conditions indicated. Both rye and potatoes are essentially European crops. Since both are efficient producers of carbohydrates under conditions of light soils and moderate to low temperatures, it is not surprising that their regions of distribution in Europe are practically coincident. While the potato occupies a prominent place in the American diet, the per capita annual consumption is considerably lower in the United States than in western Europe, amounting to only two to three bushels as compared with two to three times that much in the countries of northwestern Europe.

The potato occupies an important place in human nutrition. Stuart (18) points out that "the average world production of potatoes far exceeds that of the cereals." This statement is supported by a listing of the production of the world's important food crops for the five-year period of 1930–31 to 1934–35. In that period the aggregate production of the important food crops expressed in millions of tons amounted to 226.86 for potatoes, 165.00 for wheat, 128.60 for corn, 108.56 for rice, 69.30 for oats, 53.06 for barley, 51.84 for rye, and about 6.00 for beans. Since statistics on some of these crops are quite fragmentary, the figures given are subject to a considerable error. It must be pointed out in interpreting them that the high figure given for potatoes is not directly comparable to those presented for the cereals and for beans in that the tubers of potatoes contain much more water

than the seeds of the other crops enumerated. According to Fitch and Bennett (8), the potato contains 78.3 per cent of water. The percentage of water in the tubers varies to quite an extent with environmental conditions, but remains high under all conditions of culture. The cereals contain about 13 per cent of water. In comparing the potato and wheat crops of the world on the basis of amounts of dry matter produced by each, using 78 per cent of water in potatoes and 13 per cent of water in wheat, the relative production of potatoes is cut down from 226.86 to 49.91 millions of tons, while the world wheat crop is adjusted down from 165.00 to only 143.55 millions of tons of dry matter. Thus, on the basis of relative amounts of dry matter produced, wheat, corn, and rice are of greater importance as world food crops than is the potato. Even the oat plant produces a greater amount of dry matter than the potato. However, oats contain around 30 per cent of hull which is of no value as food and little value as feed.

The above should not be interpreted to mean that the potato is less efficient in the production of human food than the cereals. That is decidedly not the case. The world wheat acreage may be estimated at 314 millions of acres as contrasted to only 48 millions of acres used in potato production. In its optimum environment the potato is able to supply more human food per unit of area than can be produced from any of the cereals. The relative importance of the potato and also of rye in the agriculture of the United States and in northwestern Europe merits mention. The United States with its greater population produces only 4.89 and 1.69 per cent of the world's potato and rye crops as compared to the German production of 27.96 per cent of the world's potato and 21.65 per cent of the world's rye crop. On the other hand, the United States is far ahead of Germany in the production of corn and wheat. The reasons for this are found in differences in climate, soil, and economic conditions. Climatic and soil conditions over vast areas of the United States are more favorable to cereal than to potato production. In addition, the masses of northwestern Europe not infrequently find it necessary to survive on the cheapest food that can possibly be obtained. There is no doubt that the introduction of the potato contributed materially to the very rapid increases in the population of western Europe during the past 150 years. The very fact that the potato is able to produce an abundant crop

under conditions where wheat will yield but scant returns has made it possible for the bleak, sandy plains of northwestern Europe to support dense populations. As stated by Smith (13), "The potato has revolutionized Europe."

It is necessary to point out one more feature regarding the relative production of potatoes in the United States and in Germany. Germany produces almost six times as many potatoes as the United States. This does not mean that the German population consumes six or more times as many potatoes as do the people of this country. In the United States practically the entire potato crop is grown for human consumption; in years when overproduction does not occur only culls are used for feed. So far the potato crop has found but a limited industrial outlet in this country. In Germany, on the other hand, a high percentage of the potato crop is produced for feed for livestock. The crop is especially important in the production of pork. Furthermore, the crop is extensively employed in the production of industrial alcohol, potato starch, dextrine, and other commercial products.

Industrial Uses. According to Stuart (18), around 70 per cent of the potato crop of the United States is used for table purposes. The remaining 30 per cent is accounted for in about equal proportions by culls or unsalable stock, diseased and frozen tubers and storage shrinkage, and seed for the ensuing crop. "In Germany," states Stuart, "it is claimed that only 28 per cent of a normal crop is used for table food. The balance of the crop is disposed of as follows: 40 per cent is fed to livestock; 12 per cent used for seed; 10 per cent for industrial purposes; and the remaining 10 per cent is regarded as waste, due to decay, shrinkage and other causes." While a utilization of 10 per cent of the German potato crop for industrial purposes does not sound like a very high figure, it nevertheless amounts with their high production to a quantity equal to around 57 per cent of the total crop normally grown in the United States.

The main reasons for the limited industrial utilization of the potato in the United States are that corn generally provides a cheaper source of starch than does the potato; production of corn is also more stable and for that reason provides a more dependable source of raw materials at a lower price than do potatoes; and the fact that our motor fuels have originated almost

entirely from the petroleum industry. In areas well adapted to potato production, starch can probably be produced from potatoes as economically as from corn. On the other hand, it is difficult in the industrial utilization of a product such as potatoes for manufacturers to compete on the basis of a price level determined largely by a demand for table use. Obviously, the capitalization of an industry capable of operating economically only in years of surplus production of the crop on which it depends is fraught with difficulties.

A great variety of products can be produced from the potato, such as starch, dextrine, glucose, alcohol, potato flour, and a number of dehydrated products such as dried, sliced, cubed, shredded, and riced potatoes. The conversion of the potato into industrial products has the advantage of carrying these products over from one season to another. This can, of course, not be done with the tubers which are subject to rapid deterioration after a period of storage of several months.

Historical. The potato is an American contribution to the world's agriculture. It is generally agreed that the potato originated in the central Andean region of South America. There is lack of agreement as to whether the original home of the plant was in Chile, or in Peru and Bolivia. In speaking of the wild relatives of the potato, Stevenson and Clark (15) state that "all species seem to require a cool climate, since they are found growing at high altitudes in regions near the Equator and none is known to occur under tropical conditions." The Spaniards upon their invasion of South America found the potato under cultivation and the tubers used as a common article of food by the natives in the higher and cooler regions.

According to Fuess (9), potatoes were first introduced into Europe by the Spaniards. Historical evidence shows that Philip II of Spain ordered a box of potatoes (Papas) to be sent to Spain in 1565. This shipment originated from Cuzco, Peru. A portion of this shipment was sent to the Pope in Rome, who in turn submitted some of the tubers to a sick Cardinal in the Netherlands. Like many other exotic plants, the potato was credited with medicinal qualities. Two of the tubers of this lot also came to the French botanist Charles de L'Ecluse (Carolus Clusius), who grew the progenies of these tubers in the imperial gardens at Vienna

and Frankfort. However, the potato was not described until Clusius published his *Rariorum Plantarum Historia* in 1601.

The Italians were probably the first to recognize the value of the potato. There is some indication that the crop was grown in a garden in Padua as early as 1591. Fuess (10) points out that potatoes were grown in the garden of the University of Leiden in 1594, and at Montpellier, France, in 1598. The plant was grown in other gardens as a curiosity at these early dates. Its extensive production and utilization as a food crop, however, appeared much later. Thus the Royal Society recommended its extensive cultivation in England in 1663. The crop did not become of much importance in France until after the famine years of 1793 and 1817. Also the years of scarcity of 1745, 1758, 1763, 1770–1772, and 1774 contributed much to the extensive cultivation of potatoes in central and northern Europe when the plant was found to be of value as a food crop and became the poor man's bread. Fuess (9) also points out that the gradual abandonment of the three-field system in Germany toward the end of the eighteenth century contributed materially to the extensive cultivation of potatoes in that the crop was found of value to replace the fallow in the revised sequences of cropping.

Sir Walter Raleigh is credited with the introduction of the potato into Ireland around 1580. From there the crop found its way to England and via Bermuda to the United States. It arrived in Bermuda in 1613 and in the present territory of the United States in 1622. The crop was introduced into New England from Ireland during the early part of the eighteenth century. This later introduction gave rise to the common terminology of "Irish" potato.

Climatic Relationships. The main climatic requirement of a good potato producing area is a cool growing season. Thus, according to Smith (14),

> "In the United States the potato has made its greatest development in the cooler sections of the country where the mean annual temperature is between 40 and 50 degrees Fahrenheit and where the mean temperature in July is not over 70 degrees. Furthermore, the greatest yields of potatoes per acre are in those states where the mean annual temperature is below 45 and where the mean of the warmest month is not far from 65."

Bushnell (5) shows that the average yields of potatoes in the various sections of the United States are inversely proportional to the isotherms of the highest normal temperature during the growing season of the crop. Regions with the highest normal temperature below 65°F show, according to his data, average yields of 200 bushels, as contrasted to yields of only 120 to 180 and 60 to 80 bushels per acre in areas where the highest normal temperatures during the growing seasons are 69 to 73 and above 73°F, respectively. Bushnell found in growing potatoes under controlled temperatures that high temperatures at any time after the plants emerged reduced the size of the leaflets formed and called attention to the fact that this reduction in the photosynthetic areas of the plants undoubtedly had an effect on the yields of tubers. However, yields were reduced to a greater extent than could be accounted for by this reduction in photosynthetic area. On the basis of this and respiration experiments, Bushnell suggested that "deficiency of carbohydrate arising from excessive respiration may be very generally the limiting factor in plant growth at temperatures above the optimum." The rate of respiration of potatoes, as well as of other plants, increases materially with increasing temperatures. High night temperatures are especially unfavorable to the potato. The downward trends in yields from northern to southern producing areas both in North America and in Europe can be largely attributed to the increasing summer temperatures encountered in going from northern to southern areas in these continents. An abundance of sunshine during the growing season is highly desirable insofar as this influences the efficiency of assimilation of carbohydrates and reduces the rate of spread of fungus diseases attacking the foliage of the plants.

Potato yields are affected adversely by high temperatures, especially during the time the crop is developing its tubers. In regions where the season is sufficiently long and where lack of moisture does not become a limiting factor as the season advances, the critical period during tuber formation may be avoided or at least minimized by delaying the date of planting of the crop. However, when the planting date is delayed too long the temperature factor is again encountered in germination and in the attainment of a desirable stand. Thus Werner (20), working in northwestern

Nebraska, reports a mean final stand of plants of 93.0 per cent from mid-May as compared to stands of only 79.5 per cent from late-June plantings. Fitch (7) called attention to the detrimental effects of high soil temperatures to sprouting and growth. Fitch also brought out that high soil temperatures during sprouting produced especially detrimental effects if combined with high soil moisture contents.

Temperature conditions have a decided influence not only on the yield but also on the quality of the crop harvested. Quality in potatoes is especially associated with the shape and size of the tubers produced.

The production of well-shaped tubers acceptable to the market demands a set of environmental factors favoring the uninterrupted development of the tubers. Interruptions in development may be due to unfavorable temperature or moisture relationships, and not infrequently to both. Any condition causing cessation of development followed by conditions favoring growth may produce second growths resulting in knobby and poorly shaped tubers.

Potatoes are quite efficient in the utilization of moisture. Nevertheless, it is essential that a sufficient amount of moisture be available for the use of the plants during the growing season and especially after the tubers have started to form. This demands under most conditions a rainfall of not less than ten inches during the growing season. The highest yields are obtained under cool and humid conditions. The high yields obtained in Maine and in northern Europe are directly traceable to the cool, humid climates of these areas which provide the ecological optimum for potato production. In the United States as well as in Europe higher temperatures and less reliable moisture conditions are encountered from north to south. These progressive changes in temperature and moisture conditions account for the location of the optimal, moderate, and minimal areas of potato production in these two important potato growing continents. In the production of early potatoes in southern areas the crop is grown during the cooler and generally moister portion of the year. Furthermore, in southern producing areas early-maturing varieties are used. The crop is usually harvested before attaining full maturity.

Excessive moisture as maturity approaches not only leads to difficulties in harvesting the potato crop but also increases damage

from diseases and lowers the quality of the tubers. High humidity results in severe losses in the potato crop due especially to the ravages of the late blight fungus (*Phytophthora infestans*).

The high yields of potatoes obtained on the higher plateaus of the intermountain region of the United States are accounted for by the relatively low temperatures prevailing at the high elevations, and the controlled water supply by means of irrigation.

Soil Relationships. The potato crop of the world is grown over a wide range of soil conditions. Edaphic relationships are generally speaking of less importance in limiting yields of the crop than the climatic factors of the environment. Nevertheless, the soil factors influence yield, length of time required for the crop to attain maturity, eating quality, keeping quality, and the extent of loss from diseases. The general soil requirements of the potato are set forth by Morgan *et al.* (12) and cited in the following paragraph.

> "Loam, fine sandy loam, or silt loam soils having deep, mellow subsoils with especially good underdrainage are most desirable. The crop requires moist soil conditions at all times, without any tendency toward poor aeration. A high state of chemical fertility must be either naturally present or artificially provided. The potassium requirements are relatively high. The crop does well over a considerable range of soil reaction. In the Northeast, where scab-sensitive varieties are grown, reactions between *p*H 4.8 and 5.4 are considered best. Much of the western production, however, is on less acid or slightly alkaline soils."

Soil conditions over vast areas of the important producing regions of northwestern Europe are not naturally ideal for potato production. They have, however, been modified by cropping and cultural practices, as well as by heavy applications of fertilizers, so that relatively high yields are obtained. It is the generally favorable climatic conditions prevailing in these areas that make possible the extensive utilization of these rather light, sandy soils. Likewise, sandy soils can and are being used for potato production in areas where moisture conditions can be controlled by irrigation. But again, agronomic practices leading to the building up of the organic matter contents of these light soils materially increase yields and lend stability to production. Potatoes also respond well to organic matter applications to heavy soils. Soil structure as well as texture has a marked relationship to the quality of the tubers produced.

Muck and peat soils when properly managed can be used to advantage in potato production. As stated by Thompson (19), "There is some prejudice against the quality of muck-grown potatoes, but this is probably not justified as potatoes of excellent quality are being grown on well-drained and properly fertilized soils of this type."

World Distribution. The world's important potato producing areas are practically confined to two continents, Europe and North America, with the former producing 91.80 and the latter 5.91 per cent of the total world crop during the five-year period 1930–31 to 1934–35. The northern hemisphere accounted for 98.72 per cent of the total world production. Climatic, soil, and economic conditions are responsible for the great preponderance of the potato in Europe.

Table 43 gives the world statistics on potato production. Only two non-European countries, the United States and Canada, are found among the first 15 producing countries of the world. The southern hemisphere is not represented. Argentina produces only 34.18 and Australia only 13.14 millions of bushels of potatoes annually.

TABLE 43. WORLD STATISTICS ON POTATO PRODUCTION: ACREAGE, YIELD PER ACRE, AND PRODUCTION IN SPECIFIED COUNTRIES, AVERAGES FOR 1930–31 TO 1934–35

Rank	*Countries*	*Acreage, in 1,000 Acres*	*Yield per Acre, in Bu.*	*Production, in 1,000 Bu.*	*Percentage of Total World Production*
1	Germany	9,335	226.5	2,114,235	27.96
2	U.S.S.R.	14,695	119.6	1,758,036	23.25
3	Poland	6,742	167.5	1,129,238	14.93
4	France	3,495	164.4	574,531	7.60
5	United States	3,426	108.0	369,907	4.89
6	Great Britain	1,098	252.3	277,062	3.66
7	Spain	1,031	167.6	172,759	2.28
8	Belgium	412	319.8	131,758	1.74
9	Netherlands	395	276.6	109,253	1.44
10	Italy	981	88.7	87,017	1.15
11	Canada	556	138.4	76,934	1.02
12	Lithuania	423	173.6	73,428	0.97
13	Sweden	331	208.1	68,888	0.91
14	Rumania	521	130.7	68,085	0.90
15	Hungary	711	91.2	64,821	0.86
	All others	3,848	—	486,148	6.44
	World total	48,000	157.6	7,562,100	100.00

Figure 85 gives the distribution of potato production in Europe. Production is centered around Germany and the former Poland. Russia is also a very important producer, but production there is not so concentrated as in Germany, Belgium, and the Netherlands.

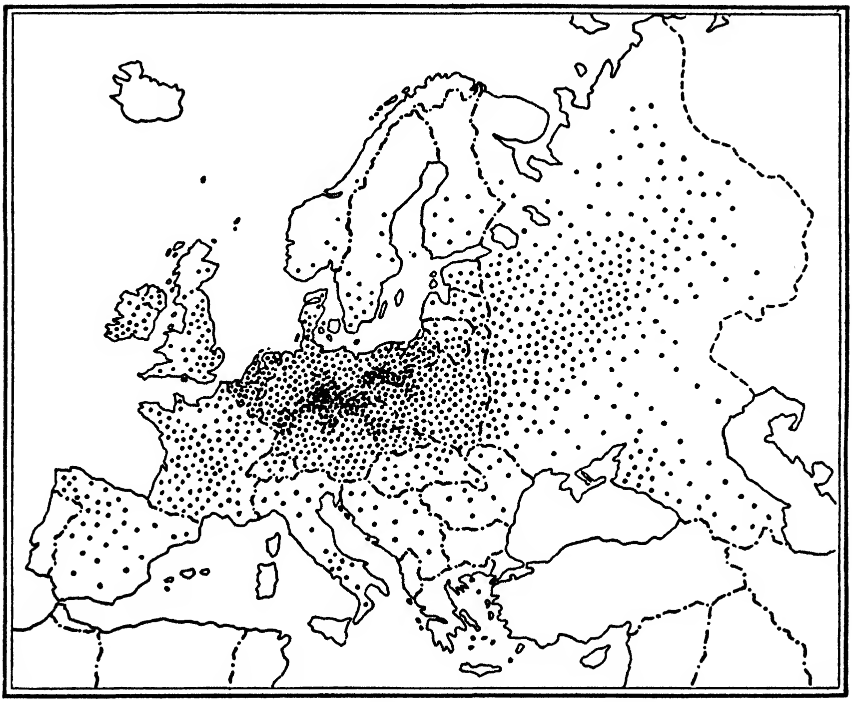


FIG. 85. Distribution of potato production in Europe. Average production for the five-year period of 1930–31 to 1934–35. Each dot represents 5,000,000 bushels.

Attention is called to the high average yields obtained in the countries of northern Europe. Belgium leads with 319.8 bushels per acre. The Netherlands, Great Britain, Germany, and Sweden follow in the order named; all have average yields of more than 200 bushels. These high yields are accounted for by favorable climatic conditions and intensive methods of cultivation.

Distribution in the United States. It is customary to classify the potato producing states according to the earliness or lateness of the bulk of production in each state and the period during which the crop is harvested. The late or main crop of the country is produced north of the Corn Belt, at higher elevations in the inter-

mountain area, and in the Pacific Northwest. The early crop is produced in the states along the Atlantic from Virginia south, and in those bordering the Gulf of Mexico. Intermediate sections of commercial importance are found in eastern Oklahoma, eastern Kansas, and northwestern Missouri, in Arkansas, Tennessee, and California.

TABLE 44. POTATOES: ACREAGE HARVESTED, YIELD PER ACRE, AVERAGE PRODUCTION FOR THE TEN-YEAR PERIOD 1928–1937, AND 1938 PRODUCTION. ACREAGES AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	States	Acreage	Yield per Acre, in Bu.	Production		
				Average 1928–1937, in Bu.	Percentage of U. S. Total 1928–1937	1938, in Bu.
	Late					
1	Maine	169	267	44,968	12.08	40,414
2	New York	236	123	29,005	7.79	26,840
3	Michigan	280	92	25,922	6.96	30,000
4	Minnesota	331	77	25,691	6.90	20,700
5	Pennsylvania	213	120	25,584	6.87	22,002
6	Wisconsin	265	88	23,380	6.28	19,080
7	Idaho	109	214	23,308	6.26	28,750
8	Colorado	102	146	14,762	3.97	11,830
9	Ohio	128	96	12,308	3.31	12,626
10	North Dakota	128	72	9,137	2.45	12,070
	Other states	634	104.9	66,494	17.87	64,707
	Total late potatoes	2,595	115.8	300,559	80.74	289,017
	Early and Intermediate					
1	Virginia	101	121	12,352	3.32	10,428
2	North Carolina	80	100	8,028	2.16	8,690
3	New Jersey	46	163	7,615	2.05	10,530
4	Missouri	57	77	4,411	1.18	5,832
5	Kentucky	50	76	3,818	1.03	4,635
6	California	17	220	3,739	1.00	9,690
7	Kansas	38	83	3,365	0.90	3,219
8	Texas	51	66	3,361	0.90	2,950
9	Maryland	31	103	3,257	0.87	2,990
10	Florida	27	110	2,995	0.80	4,488
	Other states	250	75.0	18,758	5.05	21,694
	Total early and intermediate potatoes	748	95.9	71,699	19.26	85,146
	Total U. S.	3,343	111.4	372,258	100.00	374,163

Table 44 gives the potato statistics for the leading late, early, and intermediate producing states. It is striking to find that

only one of the early-crop states ranks among the ten high producing states of the country. Over 80 per cent of the potato crop is produced in the late or northern states.

Figure 86, taken from Strowbridge (16), gives the origin of carlot shipments of potatoes in 1935. While this map shows the location of the important areas of commercial production, it does not give an entirely satisfactory picture of the general distribution of the crop. A fairly high percentage of the crop is moved by means of trucks. This holds true especially in the areas in close proximity to central markets. Also a high percentage of the crop outside of the main shipping areas is used for direct home consumption. Pennsylvania, for instance, is a high producing state; however, it does not show up prominently in Fig. 86. The potato is grown for home use in practically all sections of the United States. According to Baker and Genung (1), "No other crop, except hay, is reported from so many counties in the United States as potatoes." General production of the crop is common throughout all of the northeastern quarter of the country and especially in the areas north of the Corn Belt. Nevertheless, the commercial production of the crop is centered in fairly definite districts.

The primary reason for the great importance of the northern or late-crop section can be attributed to the favorable response of the potato to cool climates. The fact that the potato encounters less competition from other intertilled crops in cool than in the warmer areas to the south is also of importance. Thus, potatoes and corn require intensive cultivation at the same time. The most important commercial producing centers of the northern portion of the United States are Aroostook County, Maine; the Long Island and northern New Jersey districts; the western New York and Pennsylvania districts; the northern Michigan and Wisconsin districts; the Red River Valley of Minnesota and North Dakota; the western Nebraska district; the Greeley, San Luis Valley, and Gunnison and Montrose districts of Colorado; the Idaho Falls, Burley-Twin Falls, and Caldwell districts of the Snake River Valley of Idaho; and the Yakima and Wenatchee Valley districts of Washington. It will be observed from Fig. 86 that not all of these districts are located in close proximity to centers of population. The handicap of long hauls to markets from such districts must be overcome by exceptionally favorable

environmental conditions leading to high yields, and corresponding low unit costs of production, as well as by the production of a high quality potato. Both of these factors are of importance, but emphasis must be given to the production of a potato of quality to merit price premiums.

While the early and intermediate crop states produce but a relatively small proportion of the total potato crop of the United States, they are nevertheless of considerable importance in that

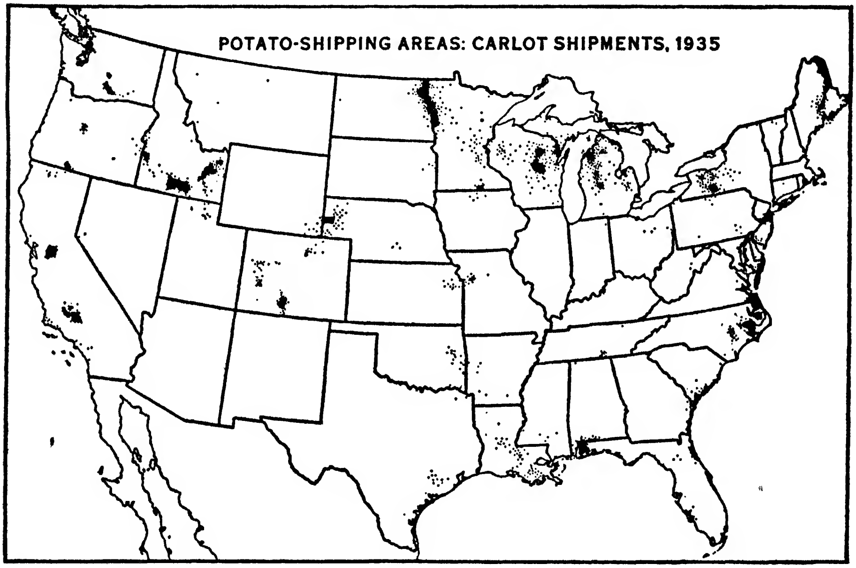


FIG. 86. Points of origin of carlot shipment of potatoes in 1935. Each dot represents 50 carloads. (After Strowbridge.)

they compete with the late crop producing areas. Early potatoes produced in Florida appear on the northern market in February and early March. At first these potatoes are more or less a luxury product, but as the season advances and the volume of southern-grown potatoes increases they come into more direct competition with the stocks of old potatoes produced in the northern states. The more important early or truck crop producing districts are enumerated by Stuart (17) as the Hastings district in Florida; the Savannah district in Georgia; the Beaufort and Charleston districts in South Carolina; Beaufort county, North Carolina; the Norfolk district and the eastern shore of Virginia; the eastern shore of Maryland; the districts centering around Louisville,

Kentucky; Columbia, Tennessee; Fort Gibson, Oklahoma; and Fort Smith, Arkansas; the Eagle Lake, Wharton, and Brownsville districts in Texas; the Alexandria and Bayou Lafourche districts in Louisiana; and the Mobile, Alabama, district.

The production of potatoes in the southern states may be expected to become of greater importance in the future. The industry has expanded during the past ten years and in view of the present cotton situation may be expected to make additional progress.

The southern early-market potato producing sections look to northern growers for a major portion of their seed stock. This has created an important and specialized industry in northern areas and at higher elevations, or in sections adapted to the production of good quality seed potatoes to supply the southern demand for relatively disease-free seed. The virus, or so-called degenerative, diseases of the potato make rapid progress under southern conditions so that it is difficult and in places impossible to produce seed stock having the same vigor as that grown in the North. Furthermore, under the temperatures prevailing in the South it is difficult to carry over seed stock from one season to the next. This is especially the case in areas where no fall crop is grown, where the seed stock would have to be carried throughout the summer months.

Long-time trend studies of the potato acreage of the United States by Strowbridge indicate a downward trend from 1911–1915, when a yearly average acreage of 3,473,000 acres was reported, until the low point of 3,123,000 acres was reached for the yearly average for the five-year period of 1926–1930. In recent years the acreage has increased somewhat. The yearly average for 1931–1935 was reported as 3,515,000 acres. The total production of the potato crop showed an upward trend because of increased yields per acre. The United States per capita production shows a definite downward trend since 1911, indicating that the increase in population has been greater in proportion than the increase in the total production of potatoes.

THE SWEET POTATO

Importance as a Food Crop. Since but a relatively small proportion of the world's sweet potato crop enters commercial chan-

nels, statistical data regarding the extent of its production are fragmentary. The crop is of importance in practically all tropical and subtropical regions where it is a standard article of food, being served baked, fried, candied, and used as a filling in pies. With improvements in handling and storage, the crop is becoming of increasing importance in northern markets. However, in most northern sections the crop must still be classified as a luxury food. The higher prices paid by consumers of sweet potatoes in northern markets are accounted for not only by the transportation charges involved in moving the crop to these markets, but by the more exacting storage conditions demanded by sweet than by white potatoes. The safe storage of sweet potatoes entails a greater outlay for facilities and a more careful handling of the crop than is the case in white potatoes. Even under the best of conditions the delivery of sweet potatoes to the ultimate consumer involves greater risks and expenditures than are encountered in marketing white potatoes.

Historical. Authorities have not been able to agree as to whether the sweet potato (*Ipomoea batatas*) originated in tropical America or in the East Indies. Many investigators consider the crop native to tropical America, and believe that it was widely distributed by early Spanish and Portuguese navigators. Chung (6), however, states that although it has not been definitely determined when the sweet potato was first introduced into Hawaii, it is thought that the crop has been under cultivation on the island since about 500 A.D.

Sir Francis Drake is credited by some authorities with the introduction of the white potato into England in 1580. This gave rise to the terminology for the white potato by Gerard in 1596 as the "potatoes of Virginia, *Battata Virginiana sive Virginianorum vel Pappus*." It is well established now that the potatoes brought by Drake from Virginia were sweet rather than white potatoes. The white potato was not grown in Virginia during the sixteenth century.

Climatic and Soil Relationships. The high temperature requirement of the sweet potato bespeaks its tropical origin. The plant requires a growing season of at least four months, but even if the season is that long the sweet potato does not produce satisfactory yields unless the nights, as well as the days, are warm for

a considerable portion of the time. For this reason around 90 per cent of the crop is produced in the 15 states south of the Mason and Dixon line. The southern half of New Jersey is the most northern area of large commercial production; the crop is of local commercial importance in southeastern Pennsylvania, and in parts of Ohio, Indiana, Illinois, and Iowa.

In northern sweet potato sections a large part of the commercial crop is grown from slips produced by sprouting the tuberous roots in warm beds of soil. The temperature of the plant bed is held more or less constant at 70 to 75°F during the greater part of the period that the plants are growing in the bed or until planting-out time. South of Virginia the crop is often propagated from vine cuttings taken from the vines of plants, originally produced from slips, after these plants have started to run.

Although the sweet potato is fairly tolerant of dry weather, it thrives best under conditions of moderate rainfall. A fair amount of moisture is desirable from the time the plants are set out in the field until the vines cover the ground. After that heavy rainfall or irrigations may cause excessive vine growth at the expense of root development. High amounts of precipitation in autumn interfere with the proper ripening of the tuberous roots. Unless the roots are allowed to mature properly storage losses are likely to be high. The sweet potato demands an abundance of sunshine.

The distribution of the sweet potato like that of the white potato is determined to a far greater extent by climatic rather than by soil conditions. The plant is rather lenient in its soil requirements. A moderate proportion of sand in the top soil, with a fairly retentive subsoil, provides ideal conditions. Whatever the soil type, it should be warm, friable, and well drained. A high level of fertility is not required. As a matter of fact, on very fertile or on heavy soils the crop tends to run to vines at the expense of the roots; moreover, the sweet potatoes formed are likely to be rough and irregular in appearance. The crop is especially well adapted to newly cleared lands, such as the cutover pine lands of the South. It can also be grown on land too poor for the successful production of cotton or tobacco.

Distribution. With the exception of the production in southern New Jersey, Delaware, and eastern Maryland practically the entire commercial crop of sweet potatoes of the United States is

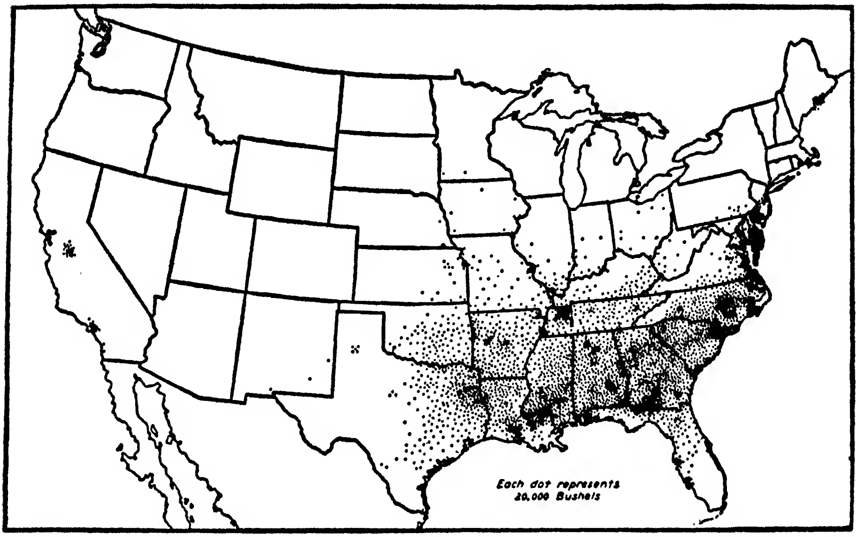


FIG. 87. Distribution of sweet potato production in the United States. Each dot represents 20,000 bushels. (After Miller.)

produced in the southeastern states. Table 45 gives the statistical data for the ten most important producing states. Figure 87, taken from Miller (11), shows the areas where sweet potatoes are grown.

TABLE 45. SWEET POTATOES: ACREAGE HARVESTED, YIELD PER ACRE, PRODUCTION — AVERAGE FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGE AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	*States*	*Acreage Harvested*	*Yield per Acre in Bu.*	*Production*		
				Average 1928–1937, in Bu.	Percentage of U. S. Total 1928–1937	1938, in Bu.
1	Georgia	111	73	8,102	11.46	9,225
2	North Carolina	84	95	7,896	11.17	8,748
3	Alabama	88	83	7,312	10.34	8,560
4	Mississippi	76	92	6,939	9.82	7,743
5	Louisiana	92	70	6,471	9.15	6,930
6	Tennessee	57	90	5,122	7.25	5,459
7	South Carolina	59	85	4,965	7.02	6,468
8	Texas	63	73	4,630	6.55	4,350
9	Virginia	37	115	4,285	6.06	3,570
10	Arkansas	38	76	2,820	3.99	3,225
	Other states	130	93.4	12,148	17.19	12,369
	Total U. S.	835	85.2	70,690	100.00	76,647

New Jersey produces around 2,000,000, Maryland around 1,300,000, and Delaware around 900,000 bushels of sweet potatoes annually. In general, New Jersey sweet potatoes are drier than those produced in the South; they are highly esteemed for their quality.

Baker and Genung list the four areas of greatest importance in commercial sweet potato production as follows: the Weakley and Henry county district in western Tennessee, the Lafayette-Opelousas district in Southern Louisiana, the Eastern Shore area of Virginia, Maryland, and Delaware, and southern New Jersey.

YAMS

Distinction between Sweet Potatoes and True Yams. Sweet potatoes differ in their texture upon cooking or baking. Certain varieties cook or bake dry and remain more or less firm while others are moist and have a soft texture. Unfortunately the term "yam" has been used quite freely in designating those varieties of sweet potatoes that cook or bake moist. The sweet potato (*Ipomoea batatas*) belongs to the morning glory family (*Convolvulaceae*); the true yams belong to the genus *Dioscorea*. As stated by Young (21), "true yams and sweet potatoes are unrelated botanically and, although the plants of both are vines and produce underground tubers or tuberous roots, neither the vines nor the tubers of the two groups bear a real resemblance to each other." The name "yam" should therefore not be applied to moist varieties of sweet potatoes.

Utilization and Distribution. The edible species of yams, according to Young, produce starchy tubers similar to the white potato in food value and taste. Young lists six species of yams; of these the greater yam (*Dioscorea alata*) is the most important as well as the most widely distributed. In general the flesh of the tubers of this species is white; certain varieties, however, have yellowish and even light or deep purple flesh. Under favorable conditions the tubers become quite large; they often weigh ten pounds or more.

The fact that the true yam requires from 8 to 10 months for the development of a good crop limits it to the very southern portion of the United States. Yams furnish a considerable part of the food supply of the peoples of many humid tropical areas. They

are used to but a limited extent outside of the tropics. The yam takes its place with taro, dasheen, and cassava in providing tropical populations with starchy foods.

VARIOUS ROOT CROPS

Importance and Uses. A great variety of root crops are grown for human food and for feed for livestock. The most important food root crops are carrots, turnips, rutabagas, and table beets. With the exception of the table beet these same crops as well as mangels and sugar beets are also produced for feed.

In 1937 over 14 million bushels of commercial carrots were harvested from 38,540 acres in the United States. According to Beattie (2), "the carrot succeeds under a wide range of climatic and soil conditions." The crop has high food value and good shipping and storage qualities. Recent investigations regarding the value of vitamins in the diet have contributed much to popularize carrots as a food crop. Carrot production is of two general classes — the northern, summer, or main crop, considerable quantities of which go into storage, and the southern or winter crop, which appears on the markets during the winter in the form of bunched carrots. The state of New York leads in the production of the main crop while California leads in the production of bunched carrots.

"Turnips and rutabagas are essentially cool-climate crops and make their most vigorous root growth at relatively low growing temperatures regardless of date of seeding" (Beattie, 4). Turnips can be grown as a spring or fall crop. In the South they are grown mainly as a late fall, winter, or early spring vegetable. In the North they are grown mainly as a fall crop for winter storage and stock feeding. Since rutabagas require a longer growing season than turnips, only one crop is usually possible in the North, this being spring-planted and harvested late in fall.

Table or garden beets are also grown under a great variety of climatic and soil conditions. They are grown for direct table use and for commercial canning. According to Beattie (3), "beets are grown in the South as a fall, winter, and spring crop and as an early summer and fall crop in the northern part of the country."

Root crops are used to but a limited extent for forage in the United States. The main reason for this is that root and succulent

crops in general have not been able to compete with the two extensively grown American silage crops, corn and the sorghums. Their production is confined more or less to cases where such succulents are in demand by specialized enterprises, as in connection with highly specialized poultry and dairy production projects. Because of the great amount of hand labor required in producing and even in preparing root crops for feeding, silage crops provide a more economical source of succulent feed than can be produced under American conditions from root crops. Root crops for forage are extensively grown in the countries of northern Europe, especially in Great Britain, Ireland, the Netherlands, Germany, and the Scandinavian countries. The cool, humid climates of these regions are conducive to the production of high yields of mangels, turnips, rutabagas, and sugar beets. Furthermore, these root crops are able to absorb a large amount of labor. The differences in the agricultural labor situation in Europe and America have much to do with the relative importance of root crops for forage purposes in these two continents.

REFERENCES

1. Baker, O. E., and A. B. Genung, "A graphic summary of farm crops," *U. S. Dept. Agr. Misc. Pub.* 267, 1938.
2. Beattie, J. H., "Production of carrots," *U. S. Dept. Agr. Leaflet* 125, 1937.
3. ———, "The culture of table beets," *U. S. Dept. Agr. Leaflet* 127, 1937.
4. Beattie, W. R., "Production of turnips and rutabagas," *U. S. Dept. Agr. Leaflet* 142, 1937.
5. Bushnell, J., "The relation of temperature to growth and respiration in the potato plant," *Minn. Agr. Exp. Sta. Tech. Bull.* 34, 1925.
6. Chung, H. L., "The sweet potato in Hawaii," *Hawaii Agr. Exp. Sta. Bull.* 50, 1923.
7. Fitch, C. L., "Studies of health in potatoes," *Colo. Agr. Exp. Sta. Bull.* 216, 1915.
8. ———, and E. R. Bennett, "The potato industry of Colorado," *Colo. Agr. Exp. Sta. Bull.* 175, 1910.
9. Fuess, W., "Die Urheimat der Kartoffel, ihre Einführung und Ausbreitung in Europa," *Die Ernährung der Pflanze,* 31:288–293 (1935).
10. ———, "Die Kartoffel als Gartenpflanze und der Nachweis ihrers ertmaligen Vorkommens in den Gärten in Europa," *Die Ernährung der Pflanze,* 34:277–281 (1938).

11. Miller, F. E., "Sweetpotato growing," *U. S. Dept. Agr. Farmer's Bull.* 999, rev. by J. H. Beattie, and H. H. Zimmerley, 1932.
12. Morgan, M. F., J. H. Gourley, and J. K. Ableiter, "The soil requirements of economic plants," *U. S. Dept. Agr. Yearbook* 1938:753–776.
13. Smith, J. R., *The World's Food Resources.* Holt, New York, 1919.
14. Smith, J. W., "The effect of weather upon the yield of potatoes," *Mo. Wea. Rev.* 43:222–228 (1915).
15. Stevenson, E. J., and C. F. Clark, "Breeding and genetics in potato improvement," *U. S. Dept. Agr. Yearbook* 1937:405–444.
16. Strowbridge, J. W., "The origin and distribution of the commercial potato crop," *U. S. Dept. Agr. Tech. Bull.* 7, 1939.
17. Stuart, W., "Potato production in the South," *U. S. Dept. Agr. Farmer's Bull.* 1205, 1931.
18. ———, *The Potato, Its Culture, Uses, History and Classification.* Lippincott, Philadelphia, 1937.
19. Thompson, H. C., *Vegetable Crops.* McGraw-Hill, New York, 1931.
20. Werner, H. O., "Tuber development in Triumph potatoes as influenced by time of planting on dry land in northwestern Nebraska," *Nebr. Agr. Exp. Sta. Res. Bull.* 61, 1932.
21. Young, R. A., "Cultivation of the true yams in the Gulf Region," *U. S. Dept. Agr. Bull.* 1167, 1923.

Chapter XXVI

SUGAR

INTRODUCTION

Sugar as a Food. The general use of sugar among the peoples of the temperate zones is comparatively recent. Nevertheless, the product rapidly passed from the status of a luxury to a virtual necessity. Most of this shift in the position of sugar in the diets of inhabitants of the temperate zone took place within the past century. In 1821, the people of the United States consumed only 8 pounds of sugar per capita. By 1850, the amount had increased to 30 pounds, and at present the amount consumed per capita per annum is above 100 pounds.

According to Brandes *et al.* (4), "sugar provides about 13 per cent of all the energy obtained from food consumed by the people of the United States." It is necessary in this connection to point out, however, that the per capita consumption of sugar in the United States is higher than in most other parts of the world. The extensive use of candies and sweet drinks no doubt contributes to the importance of sugar in the diet of the American people.

Sugar, while providing none of the nitrogenous or mineral substances required for the building up of muscle or other body tissues, is extremely economical as a source of fuel. A pound of sugar yields 1,820 calories of energy. However, sugar is not used in the diet only as a source of energy. It also imparts an agreeable flavor to food. The introduction and extensive use of coffee served greatly to stimulate the world demand for sugar.

By-products of Sugar. Not all sugar products are put on the market in the purified and crystallized form. Sirup offers one of these products. The so-called inverted sugar yields a high grade of molasses. Some of the molasses is used as a food product, some of it as feed for livestock, and some for the making of alcohol. The early rum trade played an important part in the colonial history of the United States. In addition, the sugar industry yields such

important by-products as beet tops, beet pulp, and bagasse. The first two are by-products in the production and manufacture of beet sugar. They make a valuable feed and have contributed to the development of livestock industries near beet processing plants. Bagasse, the ground and crushed stems of sugar cane, with the addition of small quantities of crude oil, is used to supply fuel to cane mills. The excess, not required for fuel, is utilized in the manufacture of cheap paper, insulating material, wall board, packing material, etc.

Competition between the Tropical and Temperate Zones. The agricultural products so far discussed are grown in either one climatic zone or another. Any competition is only indirect or to the extent that one product can be substituted for another. However, as stated by Robertson (12), "the world trade in sugar presents the interesting feature of bringing into direct competition agricultural production of tropical and temperate zones, an identical product being obtained from two widely different plants under two very diverse sets of geographical conditions." The world trade in sugar is not unique in this respect. Other noteworthy instances of such interzonal competition are found in the production of vegetable oils, starches, and fibers. Nevertheless, the position of sugar is outstanding in this respect, in that an identical product is produced, and that political factors have long played an important part in fostering its production and distribution. This is well stated by Robertson: "The production of sugar has been a peculiarly widespread national ambition from the origins of the modern cane-sugar industry under the old mercantilist colonial systems and those of the beet sugar industry in the earlier part of the nineteenth century to the present day, when it is calculated that three-quarters of the world's output receives some protection or preference." In other words, the competitive position of sugar is in many areas fortified by the creation of an artificial social environment.

Table 46 shows the race between the two rival sugars, cane and beet, during the past 85 years. It is necessary to point out that any statistical data on sugar production are subject to certain errors. Not all countries refine their sugar to the same degree of purity. Thus India produces a low grade of sugar polarizing between 50 and 60 degrees, designated as "gur." Table 46 is compiled from data presented by Palmer (11), Zimmermann (15), and from the

United States Department of Agriculture, *Agricultural Statistics*, 1940.

Since cane and beet sugar are grown under widely different conditions, they will be discussed separately.

TABLE 46. WORLD PRODUCTION OF CANE AND BEET SUGAR[1]

Year	*Cane Sugar, in Tons*	*Beet Sugar, in Tons*	*Total, in Tons*	*Percentage of Total*	
				Cane	Beet
1841–42 . . .	1,288,000	51,522	1,339,522	96.2	3.8
1850–51 . . .	1,365,905	141,478	1,507,383	90.6	9.4
1855–56 . . .	1,346,240	269,920	1,616,160	83.3	16.7
1860–61 . . .	1,447,040	393,120	1,840,160	78.6	21.4
1865–66 . . .	1,587,040	702,240	2,289,280	69.3	30.7
1870–71 . . .	1,862,560	1,008,000	2,870,560	64.9	35.1
1875–76 . . .	1,780,800	1,504,160	3,284,960	54.2	45.8
1880–81 . . .	2,140,320	1,957,760	4,098,080	52.2	47.8
1885–86 . . .	2,546,016	2,497,570	5,061,586	50.7	49.3
1890–91 . . .	2,989,168	4,139,035	7,128,203	41.9	58.1
1895–96 . . .	3,146,614	4,832,407	7,979,021	39.4	60.6
1900–01 . . .	6,633,544	6,794,972	13,428,516	49.4	50.6
1905–06 . . .	7,538,905	8,081,987	15,620,892	48.3	51.7
1910–11 . . .	9,433,141	9,587,587	19,020,728	49.6	50.4
1915–16 . . .	11,954,387	6,580,176	18,534,563	64.5	35.5
1920–21 . . .	9,367,000	4,685,000	14,052,000	66.7	33.3
1925–26 . . .	13,347,000	8,290,000	21,637,000	61.8	38.2
1930–31 . . .	13,739,000	11,539,000	25,278,000	54.4	45.6
1935–36 . . .	20,919,000	10,687,000	31,606,000	66.2	33.8
1939 *	22,067,960	12,668,165	34,736,125	63.5	36.5

* Preliminary.

SUGAR CANE AND CANE SUGAR

Historical. Man, even in the cool regions, has long been aware of the fact that some plant products, such as fruits and certain fleshy roots, contain sugar. Another natural sweet product long known to man was wild honey. As a matter of fact, throughout many centuries honey provided the chief sweetening to populations of the temperate zones. In the tropics the value of cane has long been recognized. Sirups, and possibly a crude form of sugar, have been produced in India for several thousand years. Sugar cane spread from India to adjoining countries. According to Taggart

[1] Data from 1841–42 to 1915–16 from T. G. Palmer, *Concerning Sugar, Loose Leaf Service;* 1920–21 to 1930–31 from Zimmermann, *World Resources and Industries;* 1935–1939 from U. S. Dept. Agr., *Agricultural Statistics*, 1940.

and Simons (13), it reached China around 766 B.C. The Nestorian monks at Gondishapur, at the mouth of the Euphrates River, are the first reported to have produced a white sugar, as early as 600 A.D. According to Zimmermann, "the soldiers of Alexander the Great became familiar with sugar cane when that great conqueror pushed eastward as far as India. But it was not until around one thousand years after Christ that Europe became familiar with cane sugar through the Arabs, who in turn owed their knowledge to the Persians and Hindus."

The word "sugar" (su-gur) is of Hindu origin; cane juice in India today is called "gur."

The Arabs were instrumental in fostering the growing of sugar cane in the Mediterranean area, especially in Spain and Egypt. The Crusades during the twelfth and thirteenth centuries served to spread the fame of cane sugar to western Europe. Venice built up a considerable trade with sugar and spices. During the fourteenth and fifteenth centuries, this city state had virtually a monopoly of supplying Europe with sugar. This profitable trade came to an end with the capture of Constantinople by the Turks in 1453, and the opening of an all-water route to India around the Cape by Vasco da Gama, in 1498.

The Portuguese and Spanish navigators carried sugar cane along their colonizing routes. It was introduced from Sicily and Cyprus to Madeira in 1420, and soon afterwards to the Canaries, the Azores, the Cape Verde Islands, and to the Portuguese West African settlements. Columbus carried both sugar cane and Canary Island cane growers with him on his second voyage to Hispaniola, but the growers died and this first shipment of cane seems to have been lost. A second introduction in 1506 established the crop. The first sugar in the western hemisphere was made in 1510. In 1515 Gonzales de Velosa, generally given credit as the founder of the sugar industry in the Caribbean area, erected a horse-driven mill at Rio Nigue, Santo Domingo.

The efforts of the Spanish and Portuguese colonizers contributed materially toward early sugar production. This resulted in lowering the price of the commodity and in changing the status of sugar from a luxury to a general food product. Prior to the increased production initiated by them, sugar was used chiefly in the prescriptions of physicians and in the homes of the wealthy.

Sugar cane was introduced into Louisiana from Santo Domingo in 1741. The actual production of sugar did not, however, materialize until 1791, and the first commercial production not until 1794. From then on, the sugar industry grew rapidly. Much of the acreage formerly devoted to the growing of indigo was taken over by sugar cane.

This brief discussion of the history of sugar cane would not be complete without at least some reference to the great technological advances made during the past century in the cultivation and processing of the crop. Extensive breeding work on the sugar cane plant has resulted in the development of varieties resistant to various fungous, bacterial, and virus diseases. The successful breeding for resistance against sugar cane mosaic merits special mention. The significance of this achievement is apparent when it is recognized that only such resistance makes possible the profitable production of sugar cane in many of its present areas of distribution. This is illustrated by the recent trends of cane sugar production in Louisiana. In 1926 and 1927, Louisiana produced less than 75,000 tons of raw sugar; with the development and utilization of disease-resistant varieties, production increased rapidly, exceeding 400,000 tons of raw sugar in 1937.

Climatic Relationships. Sugar cane is a strictly tropical plant. In places such as in Louisiana and Argentina the crop is grown outside of the tropics, that is, on the climatic margin of the cane sugar zone. The cane plant usually requires from 12 to 24 months to reach maturity. Even though the temperature in the Louisiana cane districts averages 81°F and the frostfree season is over 250 days, the crop is cut in an immature stage. It is, however, left standing in the field as long as temperature conditions permit so that as high a sugar content as possible may be built up. In the tropics the sugar cane plant is a perennial, producing more than one crop from one planting of seed cane. But, even in the tropics, the second crop from a planting, known as the stubble or ratoon crop, yields less than the first. For this reason, and because the restricted area available results in a pressure for food crops, the government of Java not only restricts the area devoted to cane but also prevents the practice of ratooning. In subtropical areas usually only one sugar crop is harvested from a planting.

Sugar cane requires not only a uniformly high temperature,

but ample sunshine and an abundance of moisture. Cool, cloudy weather, especially toward the end of the season, greatly interferes with the deposition of sugar in the plants. A sugar cane producing area should have from 50 to 65 inches of rain annually. The importance of an abundant supply of moisture for the crop is emphasized by Brandes *et al.* in the statement that around 85 per cent of the subnormal crops in Louisiana are attributed to drought. In Hawaii, Java, Taiwan, Egypt, British India, Peru, Mauritius, and southern Puerto Rico maximum crops are produced by supplementary irrigation. According to Brandes *et al.*, "the more nearly the weather approaches humid tropical conditions, such as heavy precipitation followed almost immediately by bright sunshine rather than a succession of overcast, cool days with drizzling rain, the better will be its effect on the rapidly growing crop." Sugar cane production extends from the Af, Cf to the Cw or from the BA′w, CA′r to the BB′r and BB′w climates.

In certain sugar cane producing areas, such as Taiwan, the West Indies, Louisiana, Mauritius, and Réunion, hurricanes or typhoons constitute a hazard to the crop, the plantations, and the sugar factories.

Soil Relationships. Sugar cane will grow on a variety of soils. Either natural high fertility or rapidly available nitrogen and an abundant supply of available nutrients supplied by commercial fertilizers are essential for maximum yields. Good cane soils have the ability to retain moisture, are deep and friable, and must have good drainage. "Sugar cane is tolerant of moderately acid to moderately alkaline conditions" (Morgan *et al.*, 7).

World Distribution. Table 47 gives the production of raw cane sugar by important producing countries and the percentage of the world total cane and all sugar produced in each country. The distribution of cane sugar production for the eastern and the western hemispheres is shown cartographically in Figs. 88 and 89.

The statistical and cartographical data presented show that the production of cane sugar is widely distributed in the tropical and subtropical regions; as a matter of fact, so much so that attempts to group the various producing areas are of little value.

A word is in order with reference to the high production of cane sugar recorded for India. Almost the entire production is in the form of gur, solidified cane juice, without much purification.

Religious scruples of a large part of the native population dictate against the use of purified sugar. The fact that the sugar is not purified creates a bias in the tabulated data presented in Table 47, which serves to overemphasize the importance of India as a sugar producing country. Even with its high production, India does not supply enough sugar to satisfy the needs of its vast population. The unprogressive methods employed in production result in low yields. Java is the main source of white sugar for India.

TABLE 47. PRODUCTION OF RAW CANE SUGAR IN SPECIFIED COUNTRIES TOGETHER WITH PERCENTAGE OF TOTAL WORLD CANE AND ALL SUGAR PRODUCTION — CANE AND BEET SUGAR. AVERAGES FOR THE FIVE-YEAR PERIOD 1930–31 TO 1934–35

Rank	Country	Cane Sugar		All Sugar
		Production, in 1,000 Tons	Percentage of World Total Production	Percentage of World Total Production
1	India *	4,909	25.54	16.81
2	Cuba	2,803	14.58	9.60
3	Java	1,731	9.00	5.93
4	Philippine Islands	1,170	6.09	4.01
5	Brazil	1,134	5.90	3.88
6	Hawaii	991	5.16	3.39
7	Puerto Rico	893	4.65	3.06
8	Taiwan	886	4.61	3.03
9	Australia **	667	3.47	2.30
10	Peru	441	2.29	1.51
11	Dominican Republic	439	2.28	1.50
12	Argentina	384	2.00	1.31
13	British West Indies	331	1.72	1.13
14	China	241	1.25	0.83
15	Mexico	240	1.25	0.82
16	United States **	236	1.23	5.59
17	Union of South Africa	236	1.23	0.81
	All others	1,491	7.75	5.51
	World total cane sugar	19,223	100.00	—
	World total beet sugar	9,979		
	World total sugar production	29,202		

* The figures for India are for the production of gur, a low grade sugar polarizing between 50 and 60 degrees.

** Produce both cane and beet sugar.

Cuba is the world's leading producer and exporter of refined sugar. According to Robertson, this important island accounted for 18 per cent of the world's production of sugar in the period of

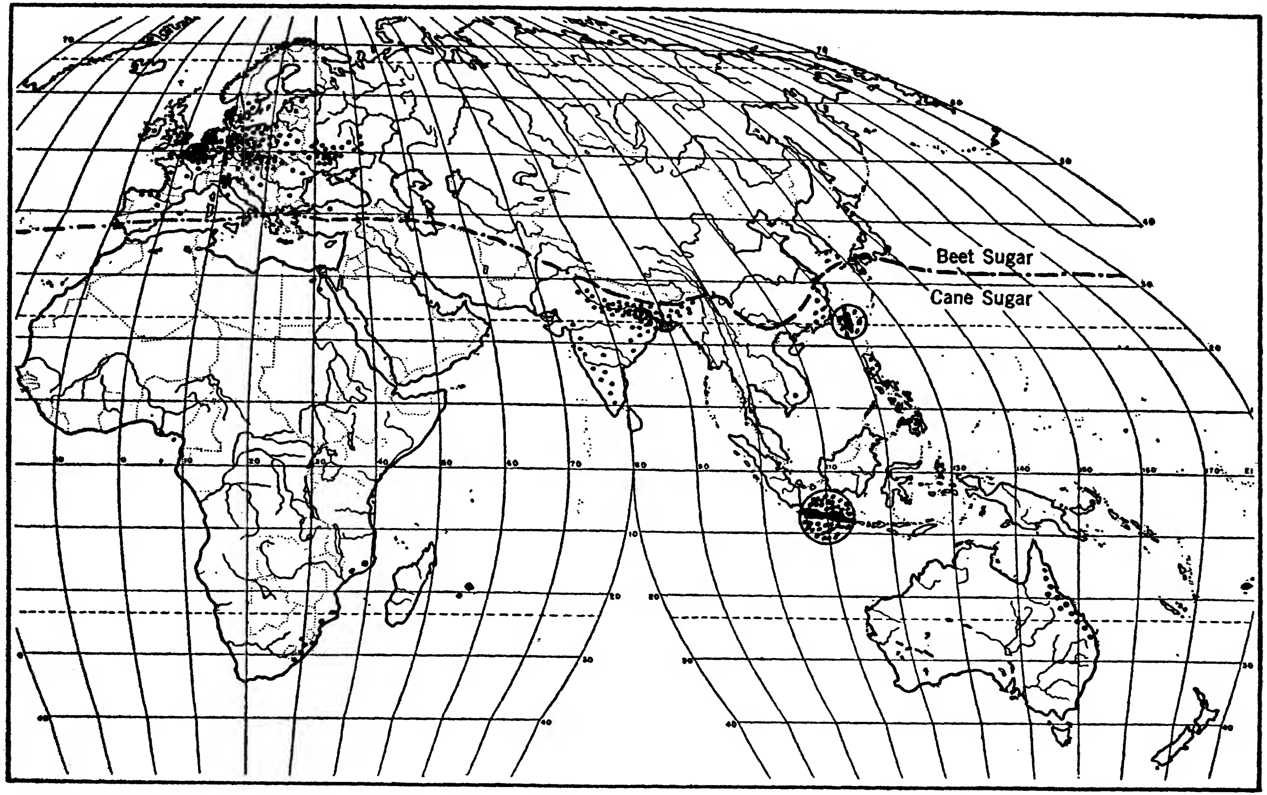


Fig. 88. Distribution of cane and beet sugar production in the eastern hemisphere. Averages for the five-year period 1930–31 to 1934–35. Each dot represents 50,000 tons of raw sugar.

1925–26 to 1929–30, and in 1925–1929 for 34 per cent of the world export of the commodity. The figure of 2.8 million tons for the period covered by the data presented in Table 47, 1930–31

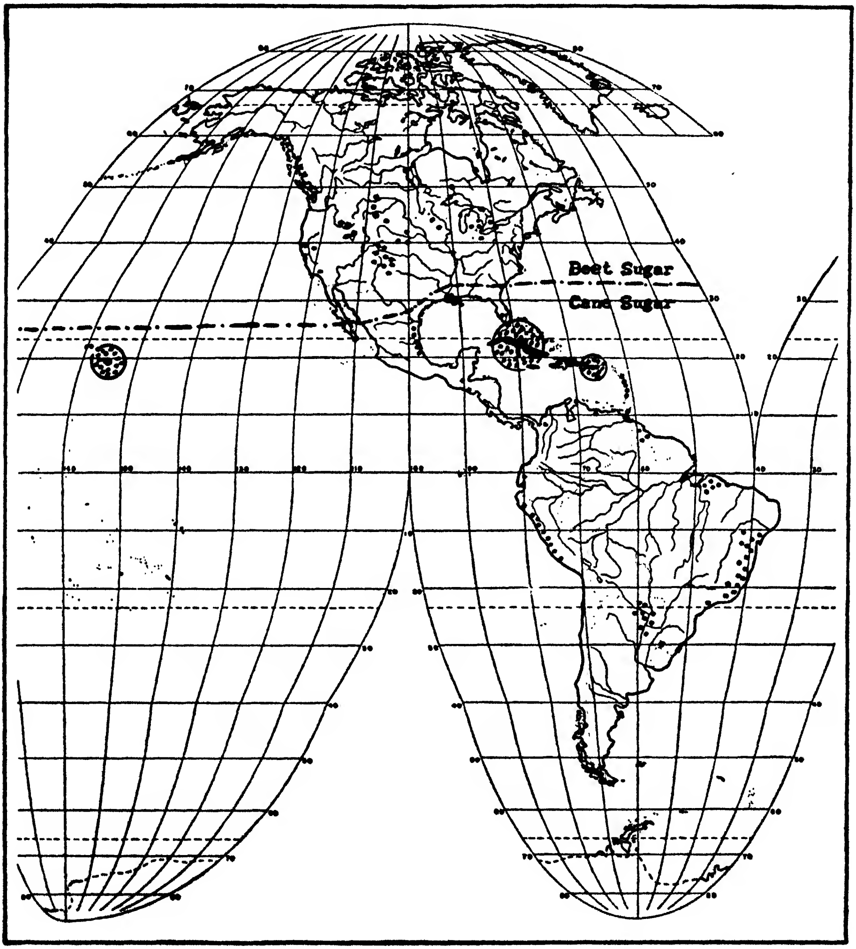


Fig. 89. Distribution of cane and beet sugar production in the western hemisphere. Averages for the five-year period of 1930–31 to 1934–35. Each dot represents 50,000 tons of raw sugar.

to 1934–35, does not do full justice to the sugar producing potentialities of Cuba. Prior to the break in world sugar prices, Cuba produced 4.1 million tons of sugar in 1918–19, 5.2 million in the season of 1924–25, and again the same high amount in 1928–29. The average annual production for the five-year period, 1925–

26 to 1929–30, amounted to 4.7 million tons. The great increase in Cuban sugar production since the turn of the century was due not only to favorable climatic and soil conditions but to no small degree to its proximity to the large and expanding markets of the United States and preferences extended to Cuban sugar producers by this country. As stated by Robertson,

> "in the period 1909–1910 to 1913–1914, the United States took 92 per cent of the island's total export of raw sugar. Under the reciprocity treaty of 1902 Cuba received a 20 per cent preference in the United States, most of which in the earlier years was actually obtained by the Cuban producers, with a consequence that North American capital flowed into the island, modernizing the mills and transport system and permitting economies of large-scale production to an unprecedented degree."

As an exporter of sugar, Java has attained a position second only to that of Cuba. Java produced an average of 2.5 million tons of sugar for the period of 1925–26 to 1929–30. Dutch colonial policies and the scientific cane-breeding work fostered by the Dutch are responsible for much of the relative importance of Java as a sugar producing territory. Production of cane in Java is an intensive enterprise; 90 per cent of the area devoted to the crop is irrigated, and large amounts of commercial fertilizers are used. Such methods and the managerial abilities of the Dutch account for the significantly higher yields than those secured in Cuba. Most of the Javanese sugar is marketed in British India and in the Far East. "Unlike Cuba, Java," states Robertson, "receives no preferential treatment but relies on a skillful sales policy." The country is favored by low labor costs. This, together with favorable climatic conditions and high unit yields, brings the costs of production to the lowest in existence.

Louisiana and Florida and the insular possessions of the United States, Philippine Islands, Hawaii, and Puerto Rico, owe their rise and continued great importance as sugar producing areas to tariff policies and free access to the United States markets.

Expansion of the industry in the Philippines has been due more to modernization of the milling side and improvements of agricultural methods of small farmers rather than to increases in acreage. According to Robertson, "soil and climatic advantages are offset by scarcity of labor and capital."

Hawaii has favorable soil and temperature conditions and the advantages of highly developed research. On the other side of the ledger, it is confronted with heavy expenditures for irrigation and fertilizer, and it lacks abundant cheap labor. Much the same conditions prevail in Puerto Rico.

Sugar production in Brazil was, quoting Robertson, "stimulated by the high prices of the years during and immediately after the war but is now faced with the problem of disposing of a surplus produced at relatively high cost. Backward methods, labor difficulties, capital shortage, and inadequate transport facilities together militate against the sound utilization of much otherwise potentially suitable sugar-cane land."

Some of the important phases of cane sugar production in the British Empire, excluding India, are summarized by Robertson in the following paragraph.

> "Australia, despite its extremely high cost of production on account of the compulsory employment of white labor, shows the most rapid increase, thanks to the embargo on sugar imports that gives a monopoly of the Australian market to the home producer. The rise in production in Natal, too, where also conditions are marginal, is due to heavy protection in the domestic market. Both countries market their surplus in Great Britain, where the preference on Empire raw sugars reduces the loss on their exports. In the British West Indies, which had already some preference in Canada, the Imperial preference has to some extent maintained and even stimulated output in recent years. In Mauritius and Fiji, conditions of production are more favorable; but both areas are approaching the limits of their potential output, and production in recent years has, with the assistance of the Imperial preference, remained fairly steady."

A feature of considerable importance to the world sugar situation and of particular import to the Far East has been the rapid and forced growth in sugar production in Taiwan (Formosa). The production of the crop was definitely stimulated by Japan to supply its needs for sugar from within its own territories, thus offering another example of the effects of intense nationalism on world crop distribution.

Sugar Cane Production in the United States. Sugar cane in the United States is grown for the production of sugar and table sirup.

Temperature limitations confine the use of the crop for the

making of sugar to the very southern parts. The most extensive sugar producing area is found in southern Louisiana. Southern Florida is of secondary importance. Southeastern Texas produces but a limited amount of cane sugar. In 1936, Louisiana harvested 227,000 acres of cane, from which 444,000 tons of raw sugar were produced. The corresponding data for Florida were 17,000 acres and 51,000 tons of raw sugar. In recent years the production of sugar cane and cane sugar has shown rapid increases in the Everglades of southern Florida. According to data presented by the

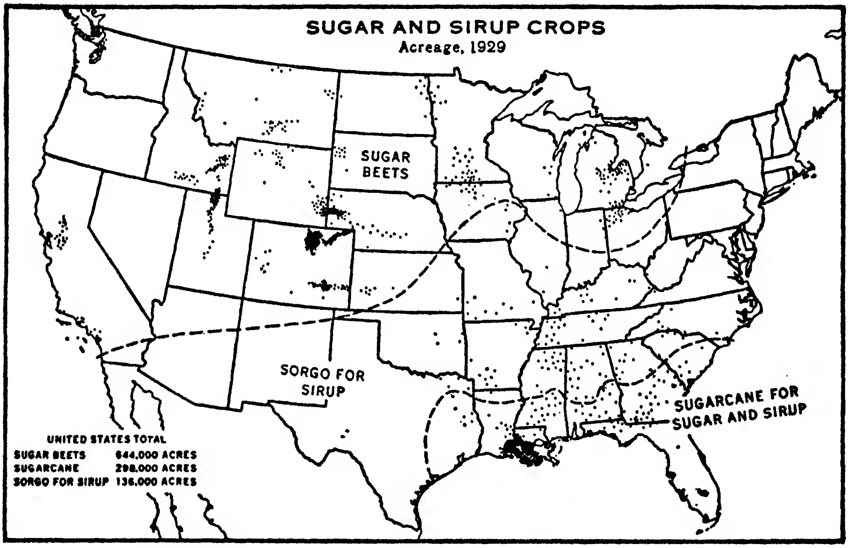


Fig. 90. The distribution of sugar and sirup crops, sugar cane, sorgo, and sugar beets in the United States. Each dot represents 1,000 acres. (After Baker and Genung.)

United States Sugar Corporation (2), production in this area increased from 745 tons of raw sugar in 1928–29 to 85,663 tons for the season of 1938–39.

Since the noncrystallizable sugars present in immature cane are desirable in sirup, the growing of sugar cane for the production of sirup is less restricted by temperature conditions. Cane is grown for the production of sirup in eastern Texas, most of Louisiana, and across to the eastern half of South Carolina. This is shown in Fig. 90, giving the distribution of sugar and sirup crops in the United States (Baker and Genung, 3).

The production of sugar cane (*Saccharum officinarum*) should not be confused with the growing of the so-called Japanese or Zwinga sugar cane (*S. sinense*), which is strictly a forage crop.

THE SUGAR BEET AND BEET SUGAR

Historical. The history of the development of the sugar beet to its present high efficiency as a producer of sugar represents one of the glowing achievements of the plant breeder. Most of the real improvement of the crop has taken place during the past century.

The German chemist, Margraff, succeeded as early as 1747 in separating sugar crystals from a number of plants. The white beet yielded the largest quantity of extracted sugar. Margraff, however, failed in his attempts to devise a method whereby extractions could be made on a large scale. This task remained for one of his students, Carl Franz Archard, who established the commercial importance of his master's discovery. With the aid of the Prussian government, the first beet sugar factory was built at Cunern, in Lower Silesia, in 1802. Archard was able to produce only a few hundred pounds of sugar daily. In view of the fact that the beets he had to work with contained only from 3 to 4 per cent of sugar, his accomplishments were quite outstanding. Archard's factory attracted the attention of Napoleon, who sent a body of scientists to inspect it. Two factories were erected in France on the strength of their report. The costs of production were high on account of the low quality of the beets available for processing and the low efficiency of the factories.

An index of the improvement of the sugar beet is provided by a record of the sugar extractions in Germany since the middle of the last century, cited from Dowling (5). By ten-year periods from 1850–1859 to 1900–1909 the extraction percentages were 7.8, 8.1, 8.6, 11.3, 13.3, 15.6. The sugar production per acre during this same period increased from 1,636 to 4,048 pounds. Much of the credit for the early improvement of the sugar beet must be given to the Frenchman, P. Louis Leveque de Vilmorin.

Beet sugar production owes much of its development and maintenance to tariffs and subsidies. Archard's original factory was built with aid from the Prussian government. Likewise, early production in France was subsidized. The Berlin decree issued by Napoleon in 1806 was aimed to keep British goods, among which

cane sugar was an important item, out of continental Europe. This gave a great impetus to sugar beet production. Then in 1811 Napoleon gave his now famous command to stimulate the production of sugar beets and proceeded to subsidize the industry, thus initiating a policy that has been followed since in most of the beet producing countries of the world to protect beet sugar from the cheaper cane sugar.

The political events of France in 1814 led to the withdrawal of the legislation designed to encourage beet sugar production; as a result, all but one of the several hundred small beet sugar factories of the country failed. The continuous support given to the beet sugar industry in Germany accounts to a large degree for the importance of this country as a world producer of sugar.

The first sugar beet factory in the United States was erected at Alvarado, California, in 1870. In 1888, only two factories were in existence; in 1892, 16; in 1908, 62; in 1915, 67; and in 1924–25, 90 factories were operating.

The relative dependence of the American and European beet sugar industry on governmental protection is briefly discussed by Robertson.

> "United States beet sugar production is much more dependent on this protection than is European production since it does not have the peculiar complex of labor conditions and the strong position in the crop rotation or, in several districts, the association with the livestock industry that give to the crop in Europe a certain independent power of resistance to adverse conditions. Given protection, further expansion is not, however, hindered by any lack of suitable soil areas."

The production of sugar beets and the beet sugar industry in general have the capacity to absorb a large amount of labor.

Climatic Relationships. A discussion of the climatic requirements of the sugar beet amounts to practically a restatement of the temperature, moisture, and light demands of the potato. The two crops are grown in the same general areas.

The sugar beet demands a temperate climate, with the mean temperature during the summer months not far from 70°F. Lill (6) points out that all the beet factories of the north-central states are located between the isotherms of 67 and 72°F mean summer temperature (May to September, inclusive). A uniform availability of moisture, supplied by either natural precipitation or irrigation,

is essential to maximum yields and high quality. Unless temperature and moisture conditions are favorable, it is difficult to produce beets of a quality for economic processing. Under adverse climatic conditions the percentage of impurities in the roots increases materially. The presence of such impurities, and especially salts, increases the costs of processing as they interfere with the recovery of sucrose. Beets suitable for processing should have a sugar content in excess of 12 per cent and a coefficient of purity of 80 per cent or more.

Long days and an abundance of sunlight are necessary for the production of a high sugar content. Chemical tests by Tottingham *et al.* (14) substantiate the practical observation that bright, autumn days followed by relatively cool nights are favorable to the storage of high percentages of sugar in the root of the sugar beet. This is the condition met with in continental areas and no doubt contributes to the quality of the beets grown in such areas, especially if the moisture conditions can be controlled by means of irrigation.

A fairly long growing season is desirable. The best beet producing areas have a growing season of around 150 days or longer. Conditions during the growing season favoring a rapid and continuous growth are highly desirable and indeed essential to the production of beets of the highest quality. The fall months should be sufficiently dry to check the vegetative growth to some extent, but not so dry as to stop it altogether. The producer in irrigated areas has the advantage over those in areas dependent on natural precipitation in that he can control the moisture supply in his fields and thus to a greater extent influence the yield and quality of the crop.

Soil Relationships. The sugar beet is grown on a variety of soils, yet the plant is quite specific in its soil requirements. Soil conditions influence both the yield and the quality of the crop. Thus, while the heavier soils usually produce the higher yields of beets, the quality of the crop produced on lighter soils is generally superior. Good yields can be obtained on certain organic soils, but again the sugar content of the roots produced on such soils is likely to be fairly low.

For best results with the crop the soil should be deep, friable, free working, and well drained. In addition the water-holding capacity should be high. It is difficult to establish full stands on

soils that are inclined to puddle. A high organic matter content, since it influences the tilth of the seedbed, is desirable. The fertility level of good beet soils should be comparatively high; furthermore, the best sugar beet soils have relatively high lime contents. While the crop is fairly tolerant with respect to soil reaction, field observations indicate that it is easier to establish and maintain full stands of beets on soils that are either neutral or slightly alkaline in reaction. According to Adams (1), sugar beets will tolerate more alkali than most field crops; however, lands heavily charged with sodium salts will not produce the best crops. Sodium sulphate is less injurious than sodium chloride or sodium carbonate.

The tonnage obtained is not determined by soil type alone. Generally, the crop does best on the heavier types of soils, such as loams, silt loams, clay loams, and with a proper organic matter content on clays; however, satisfactory yields can be obtained upon sandy loams and with favorable moisture conditions even on fairly light-textured sandy soils.

Sugar beets provide an excellent cultivated crop in the rotation, leaving the soil in good condition for the crops to follow in the sequence.

World Distribution. Like the potato, the sugar beet is essentially a European crop; around 85 per cent of the world's production is found on that continent. The reasons for this are not only climatic; economic, social, and political factors play an important part in determining the location and continuance of sugar beet producing areas. Soil conditions exert but a minor influence in limiting production.

Table 48 gives the statistical data on world beet sugar production, while Figs. 88 and 89 give the geographical locations of the producing areas in the eastern and western hemispheres.

The European beet sugar producing belt extends across the great plains of northwestern Europe from northeastern France through Belgium, the Netherlands, Germany, and Poland to the Ukraine. Significant points of concentration are found in northeastern France and the Low Countries; in the basin of the upper Elbe, the Magdeburg and Quedlinburg area; lower Silesia; Moravia and Czechoslovakia; and in the Russian Ukraine. A minor concentration area is found in the valley of the Po River in northern Italy.

TABLE 48. PRODUCTION OF SUGAR BEETS, AND RAW BEET SUGAR IN SPECIFIED COUNTRIES, TOGETHER WITH PERCENTAGE OF TOTAL WORLD BEET AND ALL SUGAR PRODUCTION. AVERAGES FOR THE FIVE-YEAR PERIOD 1930–31 TO 1934–35

Rank	Country	*Sugar Beets*			*Beet Sugar*		*All Sugar. Cane and Beet*
		Acreage, in 1,000 Acres	Yield per Acre, in Tons	Production, in 1,000 Tons	Raw Sugar, in 1,000 Tons	Percentage of Total World Production	Percentage of Total World Production
1	Germany	1,418	12.7	18,014	2,856	28.62	9.78
2	United States *	801	11.2	8,944	1,396	13.99	5.59
3	U.S.S.R.	3,144	3.7	11,680	1,371	13.74	4.69
4	France	666	12.9	8,607	1,112	11.14	3.81
5	Poland	327	9.6	3,147	546	5.47	1.87
6	Great Britain and Ireland	341	10.4	3,545	535	5.36	1.83
7	Italy	238	11.9	2,825	397	3.98	1.36
8	Belgium	133	13.7	1,824	274	2.75	0.94
9	Netherlands	111	17.0	1,886	262	2.63	0.90
10	Sweden	106	15.3	1,620	252	2.53	0.86
11	Spain *	223	7.9	1,772	216	2.16	0.80
12	Denmark	95	14.1	1,336	174	1.74	0.60
13	Hungary	128	9.8	1,134	158	1.58	0.54
14	Rumania	81	7.6	614	112	1.12	0.38
15	Yugoslavia	96	7.3	700	90	0.90	0.31
16	Canada	42	10.5	439	66	0.66	0.23
	All others	118	8.2	962	162	1.63	0.55
	World total	8,068	8.5	68,939	9,979	100.00	
	World total sugar production — beet and cane sugar						29,202

* Produce both cane and beet sugar.

The beet producing area extends from the humid marine climates of the northeastern coast of France to the continental climates of the Russian plains, that is, from the Cfb to the Dfb and the CC′r to the CB′d climates. In the west the amount of moisture is more than sufficient for the needs of the crop; as a matter of fact, cool, cloudy weather during the autumn months reduces sugar yields. In the central area conditions become drier, and light relationships more favorable. In this area are also found certain islands of Chernozem soils which are well adapted to beet culture. The Russian areas suffer from lack of precipitation during the summer

months. Favorable soil conditions counteract in part the dearth of moisture, but, as is evident from Table 48, the yields obtained are low. The low average yield of 3.7 tons of beets per acre for the five-year period covered in Table 48, 1930–31 to 1934–35, is no doubt below normal; nevertheless, while the preceding five-year period showed a somewhat higher average yield, it was still at the comparatively low level of 5.6 tons per acre. The combination of lack of sufficient moisture and higher than optimum summer temperatures in the Russian beet producing areas is also in evidence in the lower yield of raw sugar obtained per ton of beets worked as compared with areas with more favorable moisture and temperature conditions. Thus, per ton of beets worked, Poland obtains 350 pounds of raw sugar, Germany 335, and the United States 323 pounds. The yield in Russia is only 268 pounds per ton. The yield of raw sugar per ton of beets worked is also somewhat lower in areas with a marine type of climate than in those favored with a continental type. The reason for this has already been indicated.

Distribution in the United States. Table 49 gives the statistical data relating to the distribution of sugar beets and beet sugar production in the United States. Figure 90 gives the geographical distribution of the acreage.

In 1938, 23.19 per cent of the nation's sugar requirements originated from United States grown beets, as contrasted to 6.29 per cent from Louisiana and Florida cane. The balance was contributed by Cuba and the insular possessions of the United States to the extent of 28.60 per cent from Cuba, 15.41 per cent from the Philippine Islands, 14.04 per cent from Hawaii, 11.94 per cent from Puerto Rico, and to complete the circle 0.53 per cent from other sources.

The beet producing areas of the United States may be divided into three fairly distinct groups; the humid area of the North Central states, the Mountain States area, and the Pacific Coast area.

Only around 15 per cent of the country's beet sugar production is found in the humid areas of the North Central states. The two most important centers of production are the Saginaw district in eastern Michigan and the Toledo district in northwestern Ohio. Other centers of lesser importance are found around Green Bay, Wisconsin; Mason City, Iowa; Chaska, Minnesota; East Grand Forks in the Red River Valley; and Grand Island, Nebraska.

TABLE 49. SUGAR BEETS AND BEET SUGAR: ACREAGE HARVESTED, YIELD PER ACRE, AND PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937. ACREAGE AND PRODUCTION ARE EXPRESSED IN THOUSANDS

Rank	*State*	*Sugar Beets*			*Beet Sugar*	
		Acreage	Yield per Acre, in Short Tons	Produc-tion, in Short Tons	Produc-tion, in Short Tons	Percentage of U. S. Total
1	Colorado	186	12.3	2,287	339	27.38
2	California	96	13.0	1,268	208	16.80
3	Nebraska	72	12.4	888	118	9.53
4	Michigan	94	7.7	736	107	8.64
5	Montana	53	11.6	627	89	7.19
6	Utah	47	12.2	584	86	6.95
7	Wyoming	45	11.8	530	85	6.87
8	Idaho	47	10.9	517	79	6.38
9	Ohio	31	8.4	248	29	2.34
	Other states . . .	92	8.7	798	98	7.92
	Total U. S. . . .	763	11.1	8,483	1,238	100.00

The continuity of the beet belt is broken by the dry, unirrigated section of the Great Plains. But the crop assumes a place of real importance in the irrigated lands of the mountain states and the adjoining irrigated sections in the western Great Plains area. Colorado continues to be the leading state. The Utah-Idaho area is of considerable importance. Figure 90 shows the scattered areas in Wyoming and Montana.

Most of the production in the Pacific Coast area is localized in California, only one factory being located at Bellingham in northwestern Washington. Practically the entire area in California is under irrigation.

The Production of Sugar Beet Seed. Prior to the first World War practically all the sugar beet seed used in the United States was imported from Europe. Even for the five-year period ending with 1929 the annual imports of sugar beet seed from Europe averaged 12,500,000 pounds. European breeders were responsible for bringing the sugar beet up to a high standard of quality. Furthermore, under the conventional European practice of producing seed a great amount of hand labor was required. Under the labor conditions existing in the United States it was difficult to compete with European seed producers.

In 1928, Overpeck (8), working in New Mexico, showed that by taking advantage of the mild winters of the Southwest, late-summer- or early-fall-planted beets could be overwintered in the field, and satisfactory seed crops could be produced from such field plantings during the following season. This method eliminated the labor of lifting the stecklings in autumn, storing them over winter, and replanting them in spring.

Another important feature of growing seed in this country rather than importing it is that it facilitates the production of disease-resistant strains. Curly-top, a serious virus disease of the sugar beet in the United States, according to Overpeck and Elcock (9) does not occur in Europe. Consequently, no progress has yet been made by European seed breeders to breed resistant types. Several resistant strains are now being extensively grown in this country; as a matter of fact, in many of our western beet producing areas profitable beet production would be impossible were it not for the availability of these curly-top-resistant strains.

According to Overpeck *et al.* (10), it is estimated that the 1936 beet seed crop of the United States was adequate to plant from 30 to 40 per cent of the 1937 commercial beet acreage. The leading seed producing states in 1937 were Arizona, 53,478; California, 29,654; New Mexico, 19,219; and Utah, 11,602 bags of 100 pounds each. Favorable moisture conditions or irrigation are essential to getting the seedlings established in late summer.

REFERENCES

1. Adams, R. L., "The sugar beet in California," *Calif. Agr. Exp. Sta. Circ.* 302, 1926.
2. Anonymous, *Sugar in the Everglades.* United States Sugar Corporation, Clewiston, Florida, 1939.
3. Baker, O. E., and A. B. Genung, "A graphical summary of farm crops," *U. S. Dept. Agr. Misc. Pub.* 267, 1938.
4. Brandes, E. W., C. O. Townsend, P. A. Yoder, S. F. Sherwood, G. B. Washburn, L. Arner, O. E. Baker, F. C. Stevens, F. H. Chittenden, and C. F. Langworthy, "Sugar," *U. S. Dept. Agr. Yearbook* 1923: 151–228.
5. Dowling, R. N., *Sugar Beet and Beet Sugar.* Ernest Benn, Ltd., London, 1928.

6. Lill, J. G., "Sugar-beet culture in the humid areas of the United States," *U. S. Dept. Agr. Farmers Bull.* 1637, 1930.
7. Morgan, M. F., J. H. Gourley, and J. K. Ableiter, "The soil requirements of economic plants," *U. S. Dept. Agr. Yearbook* 1938:753–776.
8. Overpeck, J. C., "Seed production from sugar beets overwintered in the field," *U. S. Dept. Agr. Circ.* 20, 1928.
9. ———, and H. A. Elcock, "Methods of seed production from sugar beets overwintered in the field," *U. S. Dept. Agr. Circ.* 153, 1931.
10. ———, ———, W. H. Morrow, and R. Stroud, "Sugar beet seed production studies in southern New Mexico," *N. M. Agr. Exp. Sta. Bull.* 252, 1937.
11. Palmer, T. G., *Concerning Sugar; Loose Leaf Service.* Bureau of Statistics, U. S. Sugar Manufacturers Association, C 1-c, Washington, 1920.
12. Robertson, C. J., "Geographical trends in sugar production," *Geog. Rev.* 22:120–130 (1932).
13. Taggart, W. G., and E. C. Simons, "A brief discussion of the history of sugar cane," *La. State Dept. Agr. and Immig.*, 1939.
14. Tottingham, W. E., S. Lepkovsky, E. R. Schulz, and K. P. Link, "Climatic effects in the metabolism of the sugar beet," *Jour. Agr. Res.*, 31:59–76 (1926).
15. Zimmermann, E. W., *World Resources and Industries.* Harper, New York, 1933.

Chapter XXVII

OIL PRODUCING CROPS

INTRODUCTION

Oils and Fats. The distinction between oils and fats is a physical one, the oils being liquid and the fats solid. The concept is also relative. The materials appear either as liquids or solids, depending on whether the temperature to which they are exposed is above or below their melting points. Thus, coconut oil is liquid in the tropics but solidifies into a fat at average temperate zone temperatures.

Kinds of Oils. The term "oil" covers very different kinds of substances. They may, however, be roughly classified into three groups: mineral oils, essential or volatile oils, and fatty oils. The first, while of tremendous commercial importance, will not be discussed. The essential oils are of considerable interest to the agronomist, but owing to the special uses for which they are employed they are of less importance than the fatty oils with their great variety of uses for food and industrial purposes.

The Essential Oils. Two types of oils are derived from plants, namely, the essential and the fatty oils. The essential oils are distinguished from the fatty oils by the fact that they evaporate or volatilize in contact with the air and give off an aromatic odor, or possess a pleasant taste. All distinctly aromatic plants owe their odor to the presence of these oils. Important essential oils are turpentine, camphor, peppermint, menthol, thymol, and such perfume oils as attar of roses, ylang-ylang, neroli, bergamot, and orris. In addition, there are certain grass oils like oil of citronella, lemongrass oil, palmarosa, and oil of vetiver.

The perfume oils are of special importance in the group of essential oils. These oils are extracted from the flowers, leaves, or woods of many different species of plants in various ways depending on the quality and stability of the compounds. The usual method is by steam distillation. The origin of the important perfume oils is discussed by Hill (5) in the following paragraph.

> "Most of the natural perfumes are made in southern France, the industry centering around Grasse and Cannes in the French Riviera. In this area garden flowers are cultivated on a large scale, and from 10,000,000 to 12,000,000 pounds of flowers are gathered annually. These include 5,500,000 pounds of orange blossoms, 4,400,000 pounds of roses, 440,000 pounds of jasmine, and 330,000 pounds of violets. Large quantities of cassia, tuberoses, jonquils, thyme, lavender, and geraniums are grown, and many other fragrant species, to a lesser degree. Flowers are also grown for the perfume industry to some extent in England, Reunion, North Africa, and various European and Asiatic countries."

The use of the essential oils is by no means limited to the perfume industry; they have varied applications. Turpentine is used extensively in the paint and varnish industries. Many are used as flavoring materials or essences in candy, ice cream, soft drinks, liquors, tobacco, etc. Others have certain therapeutic, antiseptic, or bactericidal properties which make them valuable in medicine and dentistry. Still others are used as deodorants in a variety of products, as in soaps, glues, shoe polish, and printer's ink.

With the exception of three products, the United States is not an important producer of essential oils. One of these products, turpentine, is a forest product. The turpentine industry, yielding both the essential oil, or spirit of turpentine, and rosin, is closely identified with the economic development of the South. The other essential oils of considerable importance in the United States are peppermint and spearmint oils. These mints are classified as field crops. As stated by Sievers (13), this country is the principal producer of these oils.

> "England, Germany, France, and Italy produce relatively small quantities. Japan has under cultivation a vast acreage of a different species of mint which yields an oil of different quality, used largely as a source of natural menthol, of which it contains a high percentage. Accurate statistics on the world's production of mint oils are not available. In this country the production averages about half a million pounds. In 1926 and 1927 the production of peppermint oil reached approximately 700,000 pounds, but in the two years immediately preceding the crop was considerably below the average. The production of spearmint oil averages about 50,000 pounds."

Peppermint oils are produced from the species *Mentha piperita*, spearmint from *M. viridis*, while *M. arvensis* var. *piperascens* is extensively cultivated in Japan as a source of menthol.

Mint production in the United States is centered largely on the fertile muck lands in southern Michigan and northern Indiana. Around 40,000 acres are devoted to the crop in this area. Other producing centers of less importance are found on the reclaimed muck lands in the Willamette Valley of Oregon and along the Columbia River in Oregon and Washington to the extent of about 2,000 acres. The crop is also produced to a limited extent in southwestern Oregon, in the Yakima Valley of southern Washington, on the San Joaquin River lands in Tulare and King counties in California, and on the reclaimed muck lands in the Dismal Swamps section of eastern North Carolina.

The Fatty Oils. A great variety of plants produce fatty oils. These oils, while of less value from the aesthetic standpoint than the essential oils, are more stable and are of far greater value as food products and for industrial uses than the essential oils. For that reason, the term "oil" as it will be used in the remainder of this chapter will refer to the fatty oils.

So great is the variety of species of plants producing vegetable oils that even their enumeration is beyond the scope of this chapter. The reader interested in the great number of oil producing plants and in the more or less specific properties of each oil is referred to Jamieson's comprehensive book, *Vegetable Fats and Oils* (6). Table 50 gives in tabular form a list of the more important oils and their origin and outstanding properties. It will be observed that the oils are presented in two groups, those coming from trees and those from annual plants. They may also be classified as originating in the tropics, subtropics, or the temperate zone. Furthermore, certain plants, such as flax and castor beans, are grown primarily for the oil they produce. In others, such as cotton, the oil is a by-product. Again, other crops, for instance, soybeans and peanuts, may be grown for forage, for human consumption or as oil producing crops.

A tabulation of the consumption of fats and oils in the United States in 1938, including both vegetable and animal fats and oils, gives an idea of the great variety of products utilized. These products as listed by the Bureau of Agricultural Economics together with the percentage consumption of each are: butter, 24; cottonseed, 18; lard, 16; tallow, grease, and other inedible animal fats, 12; coconut, 6; palm kernel and babussa, 1; linseed, 5; tung, perilla, and viticica, 1; corn, peanut, and soybean, 6; palm, olive, rape,

TABLE 50. ORIGIN AND PROPERTIES OF SOME IMPORTANT VEGETABLE OILS

Oil	*Source*	*Properties and Uses*
I. TREES — PERENNIALS		
Coconut	Dried meat of coconut palm (*Cocus nucifera*)	A pale yellow or colorless oil, solid below 74°F, excellent for food purposes.
Palm	Fibrous pulp of the oil palm (*Elaesis guineensis*)	A white to yellowish vegetable fat, edible when fresh, used chiefly in the soap and candy industries.
Palm kernel	Kernels of the oil palm (*E. guineensis*)	A white oil used in the margarine industry; pleasant odor and nutty flavor.
Olive	Fruit of the olive (*Olea europaea*)	Good grades edible, oil golden yellow, clear, limpid, and odorless; inferior grades, greenish tinge, used for soap and lubricants.
Chinawood and Tung	Nuts of two species of Aleurites (*A. montana* and *A. Fordii*)	Quick-drying oil, extensively used in the varnish industry; forms a hard film.
Oiticica	Seeds of *Covepia grandiflora*	Quick-drying oil, extensively used as a substitute for tung oil.
II. ANNUALS		
Cottonseed	Seeds of the cotton plant	Edible after removal of gossypol. Used as salad, table oil, and in the manufacture of oleomargarine and lard substitutes. Lower grades, various industrial uses.
Corn	Embryo of maize kernels	Clear yellow oil, used in cooking and baking. Crude oil has many industrial uses.
Soybean	Seeds of soybean	A drying oil, edible after refining; inferior grades used in manufacture of candles, paints, soap, printing ink.
Linseed	Seeds of flax	A drying oil, yellow to brownish in color, acrid taste and smell; used in the making of paints, varnishes, linoleum, and printer's ink.
Peanut	Seeds of peanut	A nondrying oil, characteristic odor and taste, edible.
Perilla	Seeds of *Perilla frutescens*	Edible, but used mostly in the manufacture of cheap lacquer, Japanese oil paper, waterproof clothes, artificial leather, and printer's ink.
Safflower	Seeds of safflower (*Carthamnus tinctorius*)	A drying oil used in the manufacture of paints, varnishes, and linoleum.
Castor	Seeds of *Ricinus communis*	A nondrying oil, used chiefly as a purgative in medicine; retains a high viscosity at high temperatures and is, therefore, used as a lubricant in airplane engines.

TABLE 50 (*Continued*).

Oil	*Source*	*Properties and Uses*
II. ANNUALS (*Continued*)		
Sesame	Seeds of *Sesamum indicum*	Better grades used as substitute for olive oil in cooking and medicine and in Europe, in making margarine and other food products; poorer grades used for soap, perfumery, and rubber substitutes.
Hempseed	Seed of hemp plant (*Cannabis sativa*)	Used for edible purposes in some Asiatic countries, elsewhere chiefly as a paint oil and for making of soft soap; semidrying, greenish in color.
Poppy	Seed of opium poppy (*Papaver somniferum*)	Drying oil, pale to golden yellow when obtained from cold-pressed sound seed; used chiefly for edible purposes and to some extent in artist's paints.
Rape (Colza)	Seeds of species of Brassica, particularly *B. campestris*, *B. napus*, and *B. rapa*.	Semidrying oil from yellow to dark brown in color; refined oil edible, crude oil used in lamps, as a lubricant, in manufacture of soap and rubber substitutes.

sesame, teaseed, and others, 5; fish, 2; marine mammal, 1; and oleo, oleostearine, fish, liver, and tallow (edible), 3 per cent.

ANIMAL AND VEGETABLE FATS AND OILS

"One-" and "Two-Stage" Production of Fats and Oils. Vegetable fats and oils are produced directly as the result of the photosynthetic process and may in the broad sense be referred to as resulting from a "one-stage" production. Animal fats and oils, on the other hand, result from a "two-stage" system of production. That this reflects on the economy of production is quite evident. Each of the fats, animal as well as vegetable, has certain characteristics which determine its commercial importance. They can be and are, however, readily substituted one for the other.

The most important animal fats and oils for both edible purposes and industrial uses are butter, lard, beef and mutton tallow, oleo oil and animal stearine, and foots and inedible greases obtained as residues and by-products of the packing industry. In addition, these important products of animal husbandry are supplemented by a considerable supply of fish or marine oils.

Competition between Vegetable and Animal Fats and Oils. It is pointed out by Wallace and Bressman (18) that "corn is the most efficient plant of the temperate zones in fixing the energy of the sun's rays, and the hog is the most efficient meat animal for converting that sun energy of corn into a palatable form for human consumption." This sentence is an expression of the agricultural philosophy of the American Corn Belt. But, as brought out by Taylor (16), it is becoming necessary to distinguish between the production of protein and fat.

The obtaining of animal fats involves the more expensive "two-stage" production. These fats and oils produced by animals come in direct competition with vegetable fats and oils obtained from plants grown under cultivation in the temperate zones, and from wild nature growths and plantation plantings in the tropics. Vegetable oils have become of increasing importance in recent years as substitutes for butter and lard. Technological advances in refining, purifying, and deodorizing, and especially the widespread employment of the hydrogenation process have played an important part in altering the characteristics of vegetable oils to render them more suitable for human consumption. Vegetable oils are extensively used in human nutrition. The United States is by far the largest producer and consumer of cottonseed and cottonseed products in the world. Zimmermann (20) indicates that Europe may be roughly divided into two parts by the latitude of the Alps with regard to the type of fats and oils utilized — in the southern portion liquid oils, obtained mainly from olives and cottonseed, are generally preferred, lard, lard compounds, margarine, and butter being relatively unimportant, while in the northern portion of the continent butter has been waging a losing battle against lard and oleomargarine. Vegetable fats and oils have always been of especially great importance in the densely populated countries of southeastern Asia. Climatic conditions, religious concepts, and population pressure have conspired to make animal fats and proteins of but limited importance in this area.

OIL PRODUCING CROPS

Space does not permit the treatment of all the various oil-producing crops. The crops to be discussed are cotton, peanuts, soybeans, flax and safflower.

COTTON AND COTTONSEED OIL

Cottonseed Oil a By-product. Cotton is grown primarily for fiber. The crop produces, however, a series of valuable by-products. The by-products derived from the seed, that is, the cottonseed oil, meal, and hull, represent, according to Brown (2), a value in excess of $200,000,000 in the United States.

According to Westerbrook (19), an average ton of cottonseed yields approximately 311 pounds of crude oil, 906 pounds of meal, 520 pounds of hulls, and 143 pounds of linters.

Like other valuable agricultural by-products, those of cottonseed were formerly wasted. The present use of cottonseed is discussed by Brown in the following paragraph.

> "Prior to the advent of the cottonseed-oil mill — some 75 years ago — cottonseed was considered of little value. Some was used for planting purposes and a limited amount used for fertilizer and cattle feed, but the bulk of the seed was thrown away, piled up, and allowed to rot. Now, all seeds are carefully saved, and all, except about 20 per cent reserved for planting, are sold to the oil mill. Cottonseed is not now used as feed or fertilizer to any appreciable extent, but cottonseed meal, a meal ground from the residue left when the oil is extracted from the crushed seeds, is used very extensively as feed and to a limited extent as fertilizer. The meal is rich in protein, especially suited to dairy cattle."

Utilization of Cottonseed Oil. A great variety of products are made from cottonseed oil. The refined oil is used in the manufacture of lard substitutes, oleomargarine, as a cooking oil, and, when "wintered," as a salad oil. In the manufacture of lard substitutes, some of the oil is hardened by hydrogenation so that the finished product will have the desired degree of hardness. According to Jamieson, the approximate percentages of cottonseed oil used for various purposes in the United States are as follows: 70 per cent for shortening, 16 per cent for salad and cooking oils, 12 per cent for soap, and 2 per cent for oleomargarine. The foots coming from crude oil are used in making washing powder, grease, soap, roofing tar, composition roofing, insulating materials, oilcloth, waterproofing, cheap paint base, cotton rubber, artificial leather, and other articles.

Distribution of Production. The distribution of cotton is discussed in detail in Chapter XXVIII on fiber crops. The production

of cottonseed is more or less correlated with the production of fiber. The production of cottonseed oil in the United States has averaged around 1.5 billion pounds annually. Next in order have been linseed oil and corn oil. The production of soybean oil has been of relatively minor importance but has increased rapidly since 1928. The United States is by far the most important producer of cottonseed oil; other important producers are Egypt and India.

FLAX AND LINSEED OIL

Historical. Flax has long been grown for its fiber and seed. It is difficult to determine whether it was first grown for food or fiber. According to Dillman (4), primitive man was probably more interested in his food supply than in his raiment, and it seems probable that wild flax was first gathered for its seeds, as a source of food. Flaxseed, ground with grain or other seeds, is still used for food in Ethiopia, India, Russia, and to some extent in other countries.

The making of fine linen is an ancient art. With the advent of the cheaper cotton goods the importance of fiber flax in world trade has diminished materially until, at the present time, flax may be considered primarily as an oil producing crop. Two distinct types of flax have been developed — the seed flax and the fiber flax. The first is grown primarily for its seed and oil, the second for fiber and linen production.

Vavilov (17) considers that "the oldest regions of cultivated flax are in Asia: India, Bokhara, Afghanistan, Khoresan, Turkistan; on the coasts of the Mediterranean: Egypt, Algeria, Tunis, Spain, Italy, Greece, and Asia Minor." Vavilov is inclined to agree with De Candolle that flax may be of polyphyletic origin, that is, it developed from two or three species which united into one species, *Linum usitatissimum*. Other investigators, however, believe that the wild flax (*L. angustifolium*) may be the species from which cultivated flax originated. This wild species is native to the whole of the Mediterranean region; furthermore, as pointed out by Tammes (15), it is the only wild species that crosses readily with cultivated flax.

Dillman (4) points out that the cultivation of fiber flax was begun by the colonists in America soon after their settlements had become established. Seed flax became a crop of some importance in New

York, New Jersey, and Pennsylvania; by 1770 it was a staple article of export from New York; by 1810 numerous small linseed mills were in operation in Pennsylvania and New York. The linseed oil industry developed rapidly with the opening of new lands during the period 1850–1900. Owing to the ravages of flax wilt, flax became a pioneer crop, moving to the west through the Corn Belt and into the northern Great Plains as new lands were laid open by the flow of advancing settlements. It became a staple crop in the Great Plains area with the development of wilt-resistant varieties. The classical work of Bolley of North Dakota, showing that flax wilt was caused by a parasitic fungus, dispelled the idea that the flax crop was suitable only to new lands.

The discussion of flax in this chapter is limited to seed flax. Fiber flax will be considered in Chapter XXVIII.

Uses of Flaxseed. Seed flax is a cash crop; very little is utilized on the farms where it is grown. The two products of flaxseed are linseed oil and linseed meal. Various attempts to use the straw for the making of twine, canvas, towelings, rugs, etc., have not proved commercially important. At the present time there is some interest in the utilization of flax straw in the manufacture of cigarette paper.

Linseed oil has long been the most important source of drying oil in the paint and varnish industry. The oil is also extensively used in the manufacture of linoleum, oilcloth, printer's ink, and patent and imitation leather. According to Dillman (3), flaxseed yields from 30 to 40 per cent of its weight in oil, or in commercial crushing about $2\frac{1}{2}$ gallons ($7\frac{1}{2}$ pounds per gallon) to the bushel (56 pounds) of seed.

The residue left after the extraction of the oil from the ground, heated, and pressed flaxseed is known as linseed cake, or if ground, as linseed meal. It is a highly valued feed, especially for dairy cattle and young growing animals.

Climatic Relationships. Flax is grown as a spring-sown crop in northern latitudes. In the mild climates of the Imperial Valley of California, in southern Texas, Argentina, and in India it is sown in the fall and grown as a winter crop.

Flax has rather specific moisture and temperature requirements. Its restricted root development makes the plant highly dependent on surface soil moisture. This in part accounts for its importance in the spring and early summer rainfall areas of the northern Great

Plains of the United States and in the Prairie Provinces of Canada. The temperature during the vegetative development of the crop should be moderate. When exposed to conditions of intense sunlight during its early phases of growth, the crop becomes susceptible to heat canker. Because of this reaction and its demand for moderate temperatures, flax is grown as a winter crop in the southern latitudes and seeded as early as seasonal conditions permit in northern areas. Even though young flax plants are somewhat more susceptible to spring frosts than wheat or oats, April 1 to April 15 seedings have generally produced higher yields in the northern portion of the United States than later seedings.

Soil Relationships. The soil requirements of flax are well summarized by Morgan *et al.* (7) in the following paragraph:

> "Flax is not exacting in its soil requirements, its production depending principally on rainfall and a moderately cool climate. It is tolerant of a comparatively wide range in *p*H values. The crop is well adapted to the Chernozems of the eastern Dakotas, the Prairie soils of southern Minnesota, and the Planosols of southeastern Kansas. The crop does well also on sandy loam soils if the supply of moisture is adequate. In California, flax is grown very successfully under irrigation on sandy soils of the Imperial Valley, the so-called soft lands. In the North Central States the hazard of wilt has been overcome by the development of wilt-resistant varieties. Flax diseases are not a factor thus far in Kansas and California. Weeds are perhaps the greatest hazard to successful flax production. The control of weeds by means of crop rotation is an important practice in every area where flax is grown."

World Distribution. Table 51 gives the statistical data on the world distribution of flax, while Fig. 91 shows the distribution cartographically.

The Argentine Republic is the world's greatest producer of flaxseed. According to Bolley (1), flaxseed in Argentina is grown chiefly within the three great maritime provinces of Buenos Aires, Santa Fe, and Entre Rios, where both climatic and soil conditions are exceptionally favorable to flax production. As the interior of the country is approached, conditions become more hazardous. The crop is grown on an extensive scale and under conditions of a highly specialized agriculture. The proximity of the area to navigable waters favors export trade. The Uruguayan flax producing areas are adjacent to those of the Argentine. Much the same soil and climatic conditions prevail. For the five-year period of 1930–

31 to 1934–35 Argentina accounted for more than 50 per cent of the world's flax crop. Uruguay ranked fifth among the important producers of the crop. Argentine flaxseed is of exceptionally high quality. Renne (12) reports that Argentine flaxseed contains about one pound of oil per bushel more than domestic, northern-grown flaxseed.

TABLE 51. WORLD STATISTICS ON FLAXSEED PRODUCTION — AVERAGES FOR THE FIVE-YEAR PERIOD OF 1930–31 TO 1934–35

Rank	*Country*	*Total Acreage, in 1,000 Acres*	*Yield per Acre, in Bu.*	*Production, in 1,000 Bu.*	*Percentage of Total World Production*
1	Argentina	6,636	11.20	74,346	51.14
2	U.S.S.R.	6,724	4.44	29,836	20.53
3	India	3,136	5.44	17,064	11.74
4	United States	2,107	5.46	11,501	7.91
5	Uruguay	392	9.01	3,530	2.43
6	Canada	432	5.15	2,225	1.53
7	Poland	253	7.80	1,974	1.36
8	Lithuania	146	6.85	1,000	0.69
9	Latvia	105	5.08	533	0.37
10	Morocco	52	8.46	440	0.30
11	Rumania	55	7.54	415	0.29
	All others	—	—	2,500	1.71
	Total world production (excluding China)			145,364	100.00

Much of the Russian flax crop is grown primarily for fiber. Fiber production centers around the northeastern portion of the country. The drier central and southern areas and the Caucasus grow seed flax. It will be observed from Table 51 that a greater area is devoted to flax in the Union of Soviet Socialist Republics than in Argentina; the seed yield, however, is only 4.44 as compared to 11.20 bushels per acre for the South American republic. Nevertheless, Russia ranks next to Argentina as a world producer of flax.

India has long ranked as an important producer of flax. The crop is grown almost exclusively for seed. For the five-year period covered in Table 51, India ranked third and the United States fourth as world producers of flaxseed. The production in the United States during the period 1930–31 to 1934–35 was, however, considerably below normal owing to a series of drought years in the northern Great Plains. In the preceding five-year period the pro-

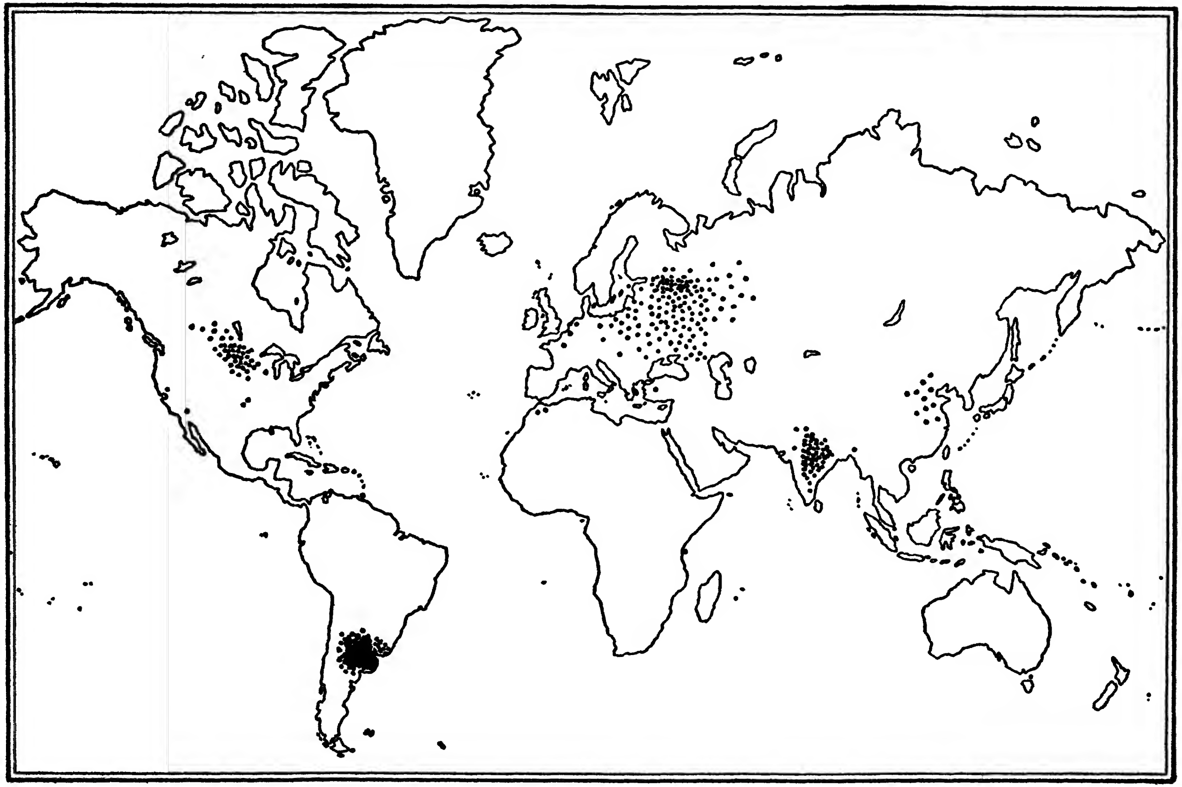


FIG. 91. World distribution of flax productions for the five-year period of 1930–31 to 1934–35. Each dot represents 250,000 bushels.

duction of the United States amounted to 20,216,000 bushels, that of India to 16,968,000 bushels. Two regions of flax production of major importance are found in India — in the Middle Ganges and the region of the Central Provinces. Flax in India is one of a group of oil producing crops, including rape, mustard, and sesame, grown for cooking and lighting purposes.

The important flaxseed producing areas of the world are concentrated in rather limited territories. Four countries — Argentina, Russia, India, and the United States — account for 91.32 per cent of the world's production of this crop. Add to these the production of Uruguay, a continuation of the Argentine region, and Canada, a continuation of the United States flax producing area, and 95.28 per cent of the world's production is accounted for. Likewise, the Polish, Lithuanian, and Latvian areas may be considered as extensions of the Russian areas. When these are taken into consideration, it will be found that 97.70 per cent of the world's flax crop is produced in ten countries.

Production in the United States. Flax in the United States is primarily a crop of the northern Great Plains area. For the ten-year period of 1928–1937 the four states of Minnesota, North Dakota, South Dakota, and Montana produced over 94 per cent of the flax crop of the country. The crop is of some importance in eastern Kansas and western Missouri. Flax has also become a crop of considerable importance in the Imperial, San Joaquin, and Sacramento Valleys of California during the past ten years. It will be observed from Table 52 that California produced 1,728,000 bushels of flax in 1939. There is also a considerable recent interest in flax production in southern Texas and in the Salt River Valley of Arizona. The California, Arizona, and Texas crops are grown as winter crops; in the northern areas flax is spring-sown. Table 52 gives the flax statistics for the United States, while Fig. 92 shows the distribution of the crop cartographically.

The total production of flaxseed in the United States shows wide fluctuations from year to year. Thus, in 1924 the production was 31,200,000 as compared to the crop of only 5,273,000 bushels during the drought year of 1936. This great seasonal variability in the size of the flaxseed crop is accounted for by the centralization of the producing area in the Great Plains states with their highly variable grassland climates.

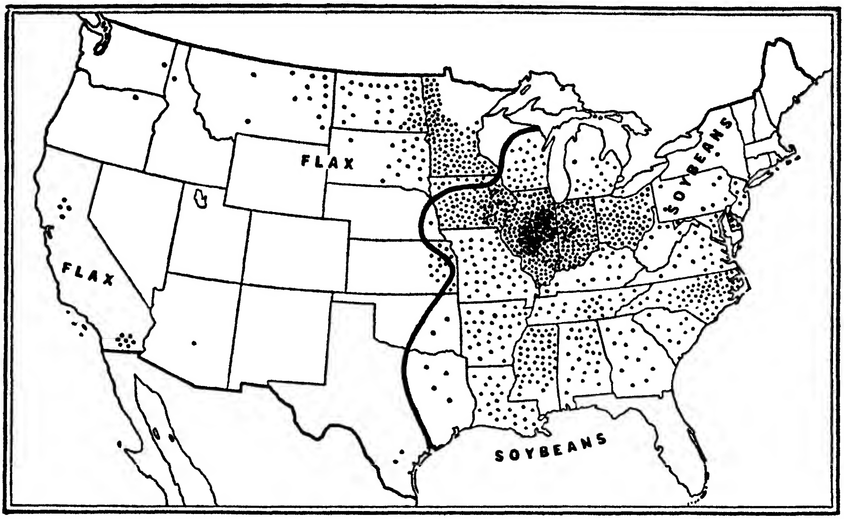


FIG. 92. Distribution of the flax and soybean producing areas of the United States in 1939. Since the acreages of these two crops overlap in Minnesota, the 171,000 acres of soybeans for that state are not shown. Each dot represents 10,000 acres.

Flax is one of the few deficiency crops grown in the United States. The consumption of flaxseed has exceeded the net domestic supply each year for a period of 30 years. In certain seasons as many as

TABLE 52. FLAXSEED: ACREAGE HARVESTED, YIELD PER ACRE, PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1939 PRODUCTION. ACREAGE AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	States	Acreage Harvested	Yield per Acre, in Bu.	Production		
				Average 1928–1937, in Bu.	Percentage of U. S. Total	1939,* in Bu.
1	Minnesota . . .	668	7.8	5,245	43.92	12,230
2	North Dakota . .	836	4.8	4,008	33.56	2,055
3	South Dakota . .	265	4.6	1,231	10.31	1,296
4	Montana	159	4.0	635	5.32	562
5	California	33 **	15.6 **	515 **	—	1,728
6	Kansas	45	5.7	257	2.15	735
7	Iowa	18	8.4	151	1.26	945
	Other states . . .	23	7.8	179	1.50	779
	Total U. S. . . .	2,035	5.9	11,943	—	20,330

* Preliminary. ** Short-time average.

20 million bushels of seed are imported. Most of the imported seed originates in Argentina, with some of it coming in from Canada. The tariff act of 1930 provides a duty of 65 cents per bushel of 56 pounds on imported flaxseed and 4½ cents a pound on linseed oil.

SOYBEANS

A Crop of Many Uses. Soybeans (*Soja max*) in the United States are grown to a greater extent as a forage than as an oil and food crop. However, from the standpoint of world production, the crop has become of considerable importance as an oil producer since the first trial shipments of seed to England in about 1908 by Japanese firms.

The entire plant of this annual legume is utilized for forage, pasturage, and soil-improvement purposes. The green beans are used to a limited extent as a vegetable. The dried beans are used for the manufacture of a great variety of human foods and livestock feeds. Piper and Morse (10) and Morse (8) present a detailed outline and discussion of the numerous uses made of the soybean, especially by the Chinese and Japanese. It is extensively utilized by these people in the place of animal fats and proteins so generally used by the people of western civilizations.

The main industrial interest in the soybean crop is centered around the utilization of the oil extracted from the seed. According to Morse, a ton of beans "containing 19 per cent of oil will yield by the extraction method about 250 pounds of oil and about 1,600 pounds of meal, and about 150 pounds is lost in cleaning, in milling, and in moisture." The oil is classified as a drying oil; its iodine numbers are, however, considerably lower than those of linseed oil — around 128 as compared to 170 to 204 for linseed oil. The oil is midway between linseed and cottonseed oil in its characteristics. Raw or crude soybean oil is used in making cores (metal molding), and for making soft soap. The oil after "boiling" is used with linseed oil in the manufacture of paints, baking japans, linoleum, oil cloth, and printing ink. According to Jamieson, "Some paint makers use ten to fifteen per cent (of the vehicle) of boiled oil, but a larger proportion of soybean oil can be used with good results." The refined oil is used in the manufacture of margarine, mayonnaise, and shortening. Soybean meal is a valuable

feed. Recently both soybean meal and soybean oil have come into use in the production of plastics.

Historical. The early history of the soybean is lost in obscurity. Chinese records written over 5,000 years ago referred to the crop. The culture of the plant in Japan is also very old.

The soybean was first introduced into the United States in 1804. The crop was tried out by various experimenters both in America and Europe toward the end of the past century. It did not, however, become of any great commercial importance until after the first World War. According to Stewart *et al.* (14), "before 1917, fewer than 500,000 acres of soybeans were grown in this country, including acreages on which soybeans were grown alone as well as acreages on which they were grown interplanted with other crops." By 1924 the acreage of soybeans grown alone had increased to over $1\frac{1}{2}$ million, and by 1938 to over 8 million acres. Preliminary figures for 1939 indicate in excess of 10 million acres.

Climatic Relationships. The soybean crop as a whole has a wide range of adaptation. This is in part due to the great differences found in the characteristics and growth requirements of the numerous varieties of the crop. Late-maturing varieties can be grown successfully only in the southern portion of the Cotton Belt, while early-maturing varieties can be grown for forage purposes in the northern portion of the Corn Belt. As stated by Morse and Cartter (9) "in general the climatic adaptations of the crop are about the same as for corn." The soybean does not, however, have as distinct a critical period in relation to its moisture demands as the corn crop. Yet while soybeans are able to withstand short periods of drought after they are well started, the crop demands a fairly uniform supply of moisture during the growing season; cool night temperatures are very effective in slowing up the development of the plants.

Soil Relationships. Soil conditions favorable to corn are normally well suited to soybeans. With proper inoculation the crop can, however, be successfully grown on soils of a lower level of fertility. The crop is also more tolerant of acid soils than either alfalfa or red clover. This fact accounts to some extent for the recent increases in the soybean acreages in the eastern portion of the United States. The crop demands only fair soil drainage, although best results are obtained on well-drained soils.

World Distribution. The world distribution of the soybean is discussed by Morse and Cartter in the following paragraph.

"The soybean is grown to a greater extent in Manchuria than in any other country in the world. It occupies about 25 per cent of the total cultivated area and is relied upon by the Manchurian farmer as a cash crop. China, Japan, and Chosen are large producers and the soybean is cultivated more or less also in the Philippines, Siam, Cochin China, Netherland India, and India. In other parts of the world, particularly Germany, England, the Soviet Union, France, Italy, Czechoslovakia, Rumania, Mexico, Argentina, Cuba, Canada, New South Wales, New Zealand, Algeria, Egypt, British East Africa, South Africa, and Spain, various degrees of success have been obtained."

The average production in specified countries for the six-year period 1931–1936 in millions of bushels of beans was as follows: China 222.6, Manchuria 155.8, United States 23.7, Chosen 21.2, Japan 11.7, and Netherland India 6.6. Data for India are not available.

Distribution in the United States. Table 53 gives the statistics of soybean production by states. Figure 92 gives the distribution of the acreage. It will be observed that the crop is of special importance in the central portion of the Corn Belt and the northern portion of the Cotton Belt. Seed production is centered around Illinois and Indiana, and also in the eastern portions of North Carolina and Virginia. Practically no soybeans are produced in the western portion of the United States. The Great Plains area is too dry for the crop. In the intermountain and Pacific coast states the soybean crop is in a poor position to compete with alfalfa for the production of forage and with the cereals for the production of concentrates. Furthermore, in much of this area temperatures are too low for the best development of the crop.

The trend in the production of seed in the United States is summarized by Morse and Cartter in the following paragraph:

"Increase in seed production has been more rapid than the expansion of acreage. In 1920, 14 states produced 3,000,000 bushels of seed, the leading states being North Carolina, Virginia, Alabama, Missouri, and Kentucky; North Carolina alone produced about 55 per cent of the total. By 1931 seed production had increased to 15,500,000 bushels, with Illinois, Indiana, North Carolina, and Missouri leading. In 1938, 57,665,000 bushels of seed were produced, of which 51,316,000 bushels (90 per cent) were harvested in Illinois, Indiana, Iowa, Missouri, and Ohio; Illinois alone produced 55 per cent of the total."

TABLE 53. SOYBEANS: TOTAL ACREAGE, ACREAGE HARVESTED, YIELD PER ACRE, PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1939 PRODUCTION. ACREAGE AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	States	Total Acreage	Acreage Harvested for Beans	Yield per Acre, in Bu.	Production		
					Average 1928–1937, in Bu.	Percentage of U. S. Total	1939,* in Bu.
1	Illinois	1,213	648	17.6	11,678	53.48	45,423
2	Indiana	566	199	15.6	3,162	14.48	13,962
3	Iowa	421	131	16.0	2,075	9.50	10,227
4	North Carolina	332	100	12.4	1,247	5.71	2,012
5	Ohio	202	66	16.8	1,173	5.37	9,681
6	Missouri	405	96	8.0	757	3.47	970
7	Virginia	122	20	12.1	249	1.14	375
8	Mississippi	254	28	8.3	229	1.05	648
9	Delaware	28	16	13.5	222	1.02	418
10	Arkansas	148	19	8.6	168	0.77	484
	Other states	1,043	106	8.2	873	4.01	3,209
	Total U. S.	4,734	1,429	14.7	21,833	100.00	87,409

* Preliminary.

SAFFLOWER

A New Oil Crop for the United States. Safflower has been grown for many years in India and Egypt as a source of oil and red dye. Its importance as a dye plant has declined greatly since the introduction of artificial dyestuffs; but according to Rabak (11), it is the most important oilseed crop cultivated in the Bombay Presidency of India, where from 500,000 to 600,000 acres are produced annually. It is grown extensively also in the dry areas of the Deccan of India, and to a small extent in China, Japan, Turkestan, and parts of Europe. In India the oil is used for food and in the making of soap.

Safflower oil is reported to possess good drying properties. Paints made with it show good durability and weather resistance. In addition it has been found to have distinct merits in white paints and white enamels where non-after-yellowing and permanent whiteness are desired. The feed value of the oil cakes has not been determined definitely.

Safflower grows best on deep soils, preferably on clay loams or

sandy loams. Heavy clay and sandy soils are less suitable. Extremely fertile soils are not desirable as plants on such soils produce a luxuriant growth but few flowers. The crop demands a fairly abundant supply of moisture during germination and up to the flowering period. After that less moisture is desirable. Since the young plants are frost-resistant, the crop can be grown in northern areas. Warm weather and an abundance of sunshine are desirable after the budding stage.

Because of the deficiency of drying oils, considerable interest has developed in the possibilities of safflower production in the United States. The crop has been grown experimentally in the northern Great Plains and western states. In these areas safflower must compete with flax.

REFERENCES

1. Bolley, H. L., "Flax production in Argentina," *N. Dak. Agr. Exp. Sta. Bull.* 253, 1931.
2. Brown, H. B., "A brief discussion of the history of cotton, its culture, breeding, harvesting and uses," *La. State Dept. Agr. and Immigr.*, 1939.
3. Dillman, A. C., "Production of seed flax," *U. S. Dept. Agr. Farmers' Bull.* 1328, 1924.
4. ———, "Improvement in flax," *U. S. Dept. Agr. Yearbook* 1937:745–784.
5. Hill, A. F., *Economic Botany.* McGraw-Hill, New York, 1937.
6. Jamieson, G. S., *Vegetable Fats and Oils.* Chemical Catalog Co., New York, 1932.
7. Morgan, M. F., J. H. Gourley, and J. K. Ableiter, "The soil requirements of economic plants," *U. S. Dept. Agr. Yearbook* 1938:753–776.
8. Morse, W. J., "Soybean utilization," *U. S. Dept. Agr. Farmers' Bull.* 1617, 1932.
9. ———, and J. L. Cartter, "Soybeans: culture and varieties," *U. S. Dept. Agr. Farmers' Bull.* 1520, 1927, Revised 1939.
10. Piper, C. V., and W. J. Morse, *The Soybean.* McGraw-Hill, New York, 1923.
11. Rabak, F., "Safflower, a possible new oil-seed crop for the northern Great Plains and the Far Western states," *U. S. Dept. Agr. Circ.* 366, 1935.
12. Renne, R. R., "The flaxseed market and the tariff," *Mont. Agr. Exp. Sta. Bull.* 272, 1933.

13. Sievers, A. F., "Peppermint and spearmint as farm crops," *U. S. Dept. Agr. Farmers' Bull.* 1555, 1929.
14. Stewart, C. L., W. L. Burlison, L. J. Norton, and O. L. Whalin, "Supply and marketing of soybeans and soybean products," *Ill. Agr. Exp. Sta. Bull.* 386, 1932.
15. Tammes, T., "Das genotypische Verhältnis zwischen dem wilden *Linum angustifolium* und dem Kulturlein *Linum usitatissimum*," *Genetica*, 5:61–76 (1923).
16. Taylor, A. E., *Corn and Hog Surplus of the United States.* Food Res. Inst., Stanford University, 1932.
17. Vavilov, N. I., *Studies on the Origin of Cultivated Plants.* Leningrad, 1926 (in Russian with English summary).
18. Wallace, H. A., and E. N. Bressman, *Corn and Corn Growing.* Wiley, New York, 1928.
19. Westerbrook, E. C., "Cotton culture in Georgia," *Ga. Agr. Ext. Bull.* 469, 1939.
20. Zimmermann, E. W., *World Resources and Industries.* Harper, New York, 1933.

Chapter XXVIII

FIBER CROPS

INTRODUCTION

Economic Importance of Fibers and Fiber Crops. Next to food, clothing and shelter represent the primary necessities of life. Early man made his garments from the skins of animals, but the need of some form of clothing lighter and cooler than skins and hides early turned his attention to the use of plant and animal fibers. The use of fibers is by no means limited to clothing; they serve a great variety of purposes — cordage, ropes, bagging, canvas, automobile tires, upholstery, etc.

From the standpoint of value of the total world production, the fiber crops are outranked by various basic food products. But, in speaking of the world's most important fiber crop, cotton, Garside (9) points out that

> "most of the commodities that take precedence of it in value of output are, in the large part, used by the producers themselves, marketed within relatively small territories around the centers of production, or marketed within the countries of production. . . . In contrast, in the case of cotton, only a very small percentage of the world's crop is used by the producers, and only a minor portion of the crop is used close to the areas of production."

This point applies to most of the world's fiber crops. It makes them one of the great commodities of international trade.

Kinds of Fibers. Three general classes of fibers may be recognized on the basis of their respective origins, namely, vegetable, animal, and synthetic fibers. Each of these classes may again be broken down into groups. Thus vegetable fibers may originate as a covering of seed as in the case of cotton and kapok; from leaves as in the case of sisal and abacá; from bast as in flax, hemp, and ramie; or even from the fruit of plants as in the case of coir, the short, coarse, rough fibers obtained from the husks of the fruits of the coconut palm.

Perhaps more important than the generic classification of fibers is a classification based on use. It is not necessary, however, to become involved here in a lengthy classification. The recognition of four general classes will suffice. The first and most important class comprises the soft fibers, of which cotton, flax, and jute are the most outstanding examples. They are used primarily for making cloth and bagging. The second class, the hard fibers — hemp, abacá, and sisal — are used mainly for twine and rope. The plaiting and rough weaving fibers make up a third class. These are obtained from various species of sedges, rushes, and grasses. The fourth and final class comprises the filling fibers. Kapok is the most valuable of these stuffing materials; a considerable number of surface fibers are commonly used for stuffing pillows, cushions, mattresses, furniture, and similar articles.

Synthetic Fibers. The development of various synthetic cellulose and even glass filaments, "rayon," and "nylon" has introduced a new factor in the textile industry. It is impossible to state to what extent these synthetic fibers will replace the natural fibers. Their production has shown a significant increase during the past 20 years. All indications point toward their more extensive use. The partial withholding of American cotton from the markets of the world has definitely encouraged the use of synthetic fibers.

COTTON

Economic Importance. Cotton is by far the most important of all fiber crops. Cotton is used all over the world. While the quantity used per person varies greatly in different countries, cotton is used in one form or another by nearly all people. Huntington *et al.* (12) bring out that cotton is more widely employed and hence more widely sold and bought than any other material. The reasons for this are quite obvious: cotton goods are cheap; they can be utilized under a great variety of climatic conditions; and the fiber has excellent qualities with regard to tensile strength, elasticity, uniformity of texture, porosity, and durability.

The use of cotton is by no means limited to the making of clothing. It is employed in making twine and cordage, for stuffing, and for the manufacture of a great variety of cotton goods. The reader is also reminded of the economic importance of the valuable

by-products of cotton, namely, cottonseed oil, cottonseed meal, linters, and cottonseed hulls.

The importance of fiber crops in international trade has already been indicated. In the export trade of the United States the value of cotton far exceeds that of any other commodity. As stated by Agelasto *et al.* (1), cotton "is the chief and often the only source of income to a large proportion of the farmers in the Southern States."

Social Significance. Cotton is grown in concentrated areas. Thus Baker (2) points out that 60 per cent of the world's cotton supply is grown on less than 3 per cent of the world's land area. Vance (22) designates the Cotton Belt of the American South as one of the most highly specialized agricultural regions in the world. The economic and social life of the southern states and with it the social and economic fabric of the entire United States are affected to a considerable degree by the economic position of cotton. The three great export crops of the United States are cotton, tobacco, and wheat. Under "normal" conditions of world trade over 50 per cent of the cotton crop is exported as compared to 33 per cent in the case of tobacco and 22 per cent of the wheat produced. The tremendous importance of cotton to the economic and social well-being of the country is brought out even more forcefully by means of actual figures of the acreages devoted to the production of the net exports of some of the important crops of the United States than by the above percentages cited. Thus Dowell and Jesness (6) point out that for the 11-year period 1920–1930 these acreages were: 22,145,000 for cotton; 14,636,000 for wheat; 2,106,000 for rye; 1,505,000 for corn; 1,292,000 for barley; 593,000 for tobacco; and 220,000 acres for rice.

The extent to which cotton affects the economic and social conditions of the South is stated vividly by two journalists, E. V. Wilcox and Henry K. Webster, in the following two paragraphs cited from Vance's book, *Human Factors in Cotton Production.*

> "And what does cotton mean to the cotton states? It means life, health, happiness, and prosperity to them. In fact, nothing else matters much. If cotton is all right, all's well in the Cotton Belt. And if cotton is sick the whole South is sick. The physician can collect no bills, the merchant can sell nothing except on credit; railroads go without freight; mill operatives languish; children grow pale; every person in the street is dejected; and gloom reigns throughout the South. . . . Cotton is the

barometer that foretells the industrial fogs, squalls, and fair weather of the South.

"A good crop and a high price means more than that the farmer's wife can begin to dream of a new parlor carpet and a piano; it means that the preacher's son and the merchant's daughter can go away to college. The clerk scents a raise and cautiously inquires the price of a diamond ring for the girl whom for the past two years he has been seeing home from church. The commercial traveler is lavish with more expensive cigars than he smoked last year, reflecting that the house won't mind a bigger expense account, with orders coming in like this."

It is estimated that from 10 to 12 million persons in the United States, chiefly in the cotton growing states of the South, depend for their living on the growing, distribution, and manufacture of cotton and cottonseed, or upon industries and trades otherwise vitally related to cotton.

Historical. Investigations relative to the origin of cotton lead to the opinion that there were probably two general centers of origin of the cotton plant, one in the Old World and one in the New World. Ware (23) states that

"it is the opinion of some investigators that there might have been two centers of origin in the Old World, Indo-China and tropical Africa, and that in the New World cotton might have either originated independently in two regions — Mexico or Central America, and the foothills of the Andes Mountains of South America — or have developed along different lines in these two regions. . . . the cultivated cottons of today seem to trace back to cottons grown in ancient times in one or another of these four world centers. Archeological specimens indicate very ancient usage of cotton in Mexico and in South America, and indigenous species in the Old World furnish some evidence of the double origin in that hemisphere."

American and Asiatic cottons have probably remained distinct since their origin. They are still so incompatible that crossing between them is rare, and persisting fertile hybrids are unknown. American cottons have 26, the Asiatic species only 13 chromosomes.

The probable origin of the three types of cotton grown in the United States is discussed by Ware in the following paragraph.

"There are many different types and a number of different species of both Old World and New World cottons, however, and all of the cultivated forms of New World origin seem to cross readily with each other, although those that originated in South America are genetically quite different in many respects from those more recently introduced

from Mexico. While the three types of cotton now grown in this country — sea island, American-Egyptian, and upland — are all probably of American origin, it would seem that the sea island and the American-Egyptian originally came from South America and that all of the upland varieties either came originally from Mexico or at some time in the past arose from crosses of Mexican and South American species. Hybridization of North and South American species especially may account for some of the upland long staple varieties."

Cotton has long been grown and used for making clothing not only in South and Central America but also in Asia and especially in India. Cotton constituted one of the important crops of the southern states almost from the date that the respective colonies were founded. It, together with the growing of tobacco and indigo, was closely correlated with the economic development of these states. Production of cotton in the southern states increased, according to Brown (4), from 73,222 bales in 1800 to 1,061,821 bales in 1835; 3,220,782 in 1855; 4,302,818 in 1875; 10,266,527 in 1900; to the record crop of 17,977,374 bales in 1926.

Even a brief history of cotton cannot disregard the effects of technological improvements made in the spinning and ginning of cotton. The main inventors of cotton machinery may be listed as John Day, inventor of the flying shuttle in 1732; James Hargreaves, spinning jenny, 1767; Richard Arkwright, water frame, 1769; Samuel Crompton, spinning mule, 1779; Edmund Cartwright, power loom, 1787; and Eli Whitney, cotton gin, 1793. This outstanding array of developments during the second half of the eighteenth century had a profound effect on the economic production of cotton and on the greater utilization of cotton goods; they brought cotton goods within the reach of the masses of all lands.

It is interesting to note that American cotton production increased very rapidly throughout the nineteenth century. Production was curtailed only temporarily by the Civil War. In 1860 England obtained 2,580,700 bales, or about 80 per cent of her total cotton supplies, from the southern states. The reduction of supplies from the South during the Civil War was the chief cause of the Lancashire cotton famine of 1861–1865. During this period, British and Continental agencies were active in investigating the possibilities of cotton production in many tropical areas, but, as pointed out by Henderson (10), with only temporary success in

most of these areas. The shortage of cotton in Europe in the early sixties greatly stimulated Egyptian and to some extent Indian cotton production. With the close of the Civil War the United States soon regained its preeminent position as a producer of cotton. The phenomenally rapid rise of American cotton production throughout the nineteenth century is accounted for by the new and rapidly increasing demands for cotton, by the rapid strides made in the development and improvements of cotton and textile equipment and processing machinery, by the large expanses of land available for agricultural exploitation, by the great improvements in the means of transportation, and last but not least by the availability of cheap labor. Labor was available and cheap both before and after the Civil War. Cotton and cotton culture were the chief contributing causes for the rapid increases of negro populations in the southern states throughout the nineteenth century. The crop provided work for the negro and enabled him to find a place in American life. Prices of tobacco, rice, and indigo were on the decline when cotton culture came to the fore. As stated by Vance, "cotton found the plantation system on the decline; it revived and pushed this system across the southern map." The economic and social transformation occasioned by the extensive growing of cotton, in the words of Frederick J. Turner (cited from Vance), "resuscitated slavery from a moribund condition to a vigorous and aggressive life."

Classification. Cotton belongs to the genus *Gossypium*, which is made up of a number of species. Considerable disagreement exists with regard to the botanical classification of the crop. Hutcheson *et al.* (13) list the seven commonly recognized species as follows:

1. *Gossypium barbadense*, the long-staple Barbadoes, Sea Island, Egyptian, and Peruvian varieties.
2. *Gossypium herbaceum*, the varieties of India, Siam, China, and Italy.
3. *Gossypium hirsutum*, the American upland varieties.
4. *Gossypium arboreum*, found in Ceylon, Arabia, and South America.
5. *Gossypium peruvianum*, the native varieties of Peru.
6. *Gossypium tahitense*, found in Tahiti.
7. *Gossypium sandwichense*, found in the Sandwich and adjacent islands.

Commercial Types. Many commercial types of cotton are recognized in the principal markets of the world. A broad grouping

of these types into five general classes according to sources, uses, and commercial values is as follows:

1. *American Upland.* This is by far the most important of the American and of the world's cottons. "American Middling," the standard short-staple grade, is the basis of price quotations for all short-staple cottons. Over 99 per cent of the American crop is upland cotton.[1] The American upland varieties have unspotted white flowers which turn rose, pink, or red on the second day of blooming. The bolls are four- or five-locked, and the seeds are usually well covered with white, brown, or green fuzz, in addition to the lint. The staple length varies from $\frac{5}{8}$ to $1\frac{1}{4}$ inch, depending on variety and environmental conditions. In the past this general class has been broken down into upland short-staple and upland long-staple cottons with the line of demarcation at the staple length of $1\frac{1}{8}$ inch. For the five-year average of 1929–1933 only 3.54 per cent of all the upland cotton produced in the United States had a staple length of $1\frac{1}{8}$ inch or more. The longer stapled types of this cotton compete with Egyptian and American-Egyptian cottons. American upland varieties have been introduced into and are now extensively grown in other important cotton producing areas of the world.

2. *Sea Island.* This cotton is a native of South America. The plants grow tall and have slender branches, the petals are yellow with a red spot near the base. The bolls are narrowly ovoid and three-locked. In contrast to the fuzzy seeds of the upland cotton, sea-island seeds are naked and black. Fancy sea island cotton has a fiber length of 2 inches or more. It is the most valuable of the world's cottons, surpassing all other types in length, strength, and fineness of lint. Unfortunately, this cotton, because of its late maturity, is particularly subject to boll weevil damage. It is also extremely susceptible to the common bacterial blight (angular leaf spot). As a result, sea island cotton is practically extinct in this country. Prior to the arrival of the boll weevil in the territories along the coast of the Carolinas and Georgia, the United States

[1] The term "upland" has completely lost its meaning as designating the altitude or location of the land on which the cotton was produced. The term originated in the early days of cotton production in the United States when it was applied to that type of cotton which was grown on the higher land more or less distant from the seacoast, in distinction from the sea-island cotton which was grown near the coast or on islands off the coast.

produced around 100,000 bales of this high-quality cotton. A limited quantity is now grown in the West Indies. The fiber is spun into fine yarns and used largely in the manufacture of laces, cambric, and fine hosiery.

3. *Egyptian.* Egyptian cotton, while a distinct type, is similar to sea island in general appearance of the plants. The fiber is fine, silky, and strong. It varies from $1\frac{1}{4}$ to $1\frac{3}{4}$ inches in length. The fiber is usually dark-cream or buff in color. It is used especially in manufacturing goods in which great strength is required, such as automobile tire fabrics, airplane wing and fuselage covers, balloon cloths, and high-quality hosiery. Egypt furnishes the bulk of the crop.

4. *American-Egyptian.* This is Egyptian cotton produced in the irrigated valleys of Arizona and southern California. The quantity of this cotton in relation to the total cotton production in the United States is limited. For the five-year period 1929–1933 an average of only 16,800 bales of American-Egyptian cotton were produced as contrasted to 14,044,400 bales of American upland.

5. *Asiatic.* The Asiatic cottons include *Gossypium herbaceum* and several related species, *indicum*, *neglectum*, *arboreum*, and *nanking*. The staple is short, often only $\frac{3}{8}$ to $\frac{3}{4}$ of an inch in length, but strong and rather rough. Asiatic cotton is grown in southeastern and southern Asia. In many districts it is giving way to American upland types.

Climatic Relationships. Cotton is grown over a wide range of moisture conditions from the humid woodland to the summer dry grassland climates, or from the Cfa and BB′r to the BSkw and CB′d climates. In the American Cotton Belt the average annual precipitation ranges from 23 inches in western Oklahoma and Texas to 55 inches in eastern North Carolina and 60 inches in southern Mississippi. Likewise, the spring rainfall ranges from 6 inches in western Texas to 16 inches in Arkansas and southern Mississippi, being heavier in the Mississippi Valley states than in Texas or the South Atlantic states. The summer rainfall is greater in the eastern and southern portions of the Belt than in the northern and western portions. Relatively dry autumn months favor harvest and the production of a cotton of high quality. Fortunately, autumn is the driest season over practically all of the American Cotton Belt. Rains at this time of the year interfere with the maturation of the crop and lead to storm losses and to discolorations of the lint. Furthermore,

as pointed out by Smith (20), an excess moisture of cotton when ginned, whether due to rain, dew, or "greenness," makes proper ginning difficult. The ideal distribution of rainfall for cotton is of the thundershower type with several days of bright, warm weather between rains.

Moisture relationships seem to be definitely associated with the shedding, or the abscission of a variable number of the immature fruits of the cotton plant. Both soil moisture and rates of transpiration constitute, according to Ewing (7), contributing factors determining the amount of shedding. Ewing points out that a loss of approximately 60 per cent of the fruit of the plant may be considered an entirely normal occurrence. He cites data from Ball's work in Egypt showing that the average rate there is around 40 per cent; also Harland's figures for St. Vincent which indicate that only from 10 to 20 per cent of the flowers produced by sea island plants in the West Indies eventually mature. The amount of shedding taking place in cotton may also be influenced by insect and disease factors.

While the cotton crop is able to gain a place of importance in agricultural regions with considerable ranges in annual and seasonal precipitations, the crop is far less lenient with regard to variations in temperature conditions. This is to be expected in view of its tropical origin. The northern limit of commercial cotton production is quite effectively determined by the average summer temperature of 77°F. Production beyond this more or less definite temperature limit becomes profitable only during a series of years with supranormal prices. Along the northern margin of the Cotton Belt the last killing frost in spring occurs on an average around April 10, and the first killing frost in fall about October 25, so that the frostless season is about 200 days. In the southern portion of the Cotton Belt the last killing frost in spring occurs about March 10 on the average, and the first killing frost in fall seldom before November 25, the frostless season being 260 days or more in length (Agelasto *et al.*).

Hazards in Cotton Production. The cotton plant like other crop plants is subject to certain hazards. From the economic point of view both environmental and price relationships should be considered. The discussion of price variation of the commodity is beyond the scope of this chapter. That violent price fluctuations

constitute a factor must, however, be recognized. Since the ravages of insects and diseases are closely associated with climatic variations, they will not be discussed separately.

Because cotton is of such vital importance to the commerce of the world and also no doubt because the great fluctuations in the prices of the commodity affect the economic status of the cotton producer, certain writers have tended to exaggerate the natural hazards encountered in cotton production. These sentiments are voiced by such statements as the one taken from Garside: "The story of the making of a cotton crop is one of successive hopes and fears, of optimistic expectations and pessimistic forebodings"; also by the often-quoted saying that "cotton can promise more and do less and can promise less and do more than any other plant."

The degree of uncertainty attending the production of cotton is not necessarily greater than found in a good many field crops. As a matter of fact Marbury (15) points out that

> "cotton, though a sensitive plant, is of all summer-growing crops of the South about the least affected by ordinary changes in the weather. . . . Its long period of growth, fruiting and maturity affords it ample opportunity to recover from a number of temporary set-backs. During the protracted season from planting in April to the completion of the harvest in November, it is exposed to many varieties of weather, and it seems to endure the bad as well as enjoy the good."

Varying hazards are encountered in the different cotton producing areas of the world. Thus in humid areas the crop may be subject to damage from excessive precipitation with its associated evils such as low temperatures, difficulties in obtaining stands, increase in insect populations, and extra competition from weeds, while the crop grown in subhumid areas may suffer just as much from lack of moisture. There may also be compensating risks. Droughts will cut down the size of the crop, but comparatively dry weather with moderately high temperatures serves to reduce weevil population and damage from this and other insects.

Variations in climatic conditions from season to season as well as within the season determine not only the yield but also to a high degree the quality of the lint produced. Quality is determined, however, not by climatic conditions alone; the type and variety grown, as well as the soil conditions and cultural practices followed, are of great importance.

The cotton producer has at least in one instance reduced the risks encountered in his enterprise. The introduction of the boll weevil for a time threatened the cotton industry of the South. While this insect is still a factor, the challenge occasioned by its introduction and rapid spread over the Cotton Belt was met by plant breeders and producers. The type of cotton produced was gradually changed by the introduction and breeding of varieties capable of producing cotton under weevil conditions. Varieties that had long been noted for high quality were discarded with the coming of the weevil and were replaced by early-maturing short-staple sorts. The quality of these early-maturing varieties was inferior, but their early maturity and determinate habits of growth shortened the fruiting season and with it the period in which they were subject to weevil damage. The weevil problem was met; however, the many excellent varieties of long-staple upland cotton of preweevil days were sacrificed. Another means now widely employed in an attempt to enable cotton plants to "outrun" the weevil is the closer spacing of the plants in the row. This leads to the setting of fewer later squares so that a higher number of early set squares and bolls may reach maturity earlier in the season and thus escape damage. The shift in the use of land for cotton in the southeastern states from the heavier to the less fertile, light-textured soils of the uplands is also traceable to the need for earlier maturity to escape severe weevil damage.

Soil Relationships. While the outer boundaries of cotton producing areas are determined almost entirely by climatic factors, the most noticeable differences in the density of cotton acreage and variations in yield per acre within the American Cotton Belt are due principally to soil conditions (Stine and Baker, 21). The soil requirements of cotton are summarized by Morgan *et al.* (17) in the following paragraph.

> "This long-season southern crop is represented by a number of types varying considerably in their soil adaptations. It requires a soil of good moisture-holding capacity, with favorable drainage and aeration. Soils well supplied with organic matter are the most productive, although much of the southeastern area is on seriously humus-deficient soil. The crop is successfully grown at various degrees of acidity, the most favorable range being *p*H 5.2 to 7. The soils east of the Mississippi lowland are generally so deficient in available nutrients that fertilizers are used very extensively. The available nitrogen in the soil is rarely adequate,

and both phosphorus and potassium must also be supplemented from fertilizer sources. The rich, dark-colored Rendzina soils of Texas are much more fertile, and fertilization is not so extensively practiced. The breeding of cotton types especially adapted to areas of more restricted rainfall has added extensive acreages in cotton in northern Texas and western Oklahoma on soils of high mineral fertility and well supplied with available nitrogen."

World Distribution. The intensive production of cotton is concentrated in rather limited areas. It will be observed from Table 54, giving the statistics of world cotton production, that the United States stands out as by far the most important producer of the commodity, producing 56.22 per cent of all the world's cotton. Two countries, the United States and India, accounted for 73.61 per cent of the world's cotton for the five-year period of 1925–26 to 1929–30, and six countries produced 94.47 per cent of all of the world's cotton crop. Figure 93 gives the geographical distribution of world cotton production.

TABLE 54. WORLD COTTON PRODUCTION. ACREAGE AND PRODUCTION IN SPECIFIED COUNTRIES TOGETHER WITH PERCENTAGES OF TOTAL WORLD PRODUCTION FOR THE TWO FIVE-YEAR PERIODS INDICATED

Rank	Country	*Acreage, in 1,000 Acres*		*Production, in 1,000 Bales*		*Percentage of Total World Production*	
		1925–26 to 1929–30	1930–31 to 1934–35	1925–26 to 1929–30	1930–31 to 1934–35	1925–26 to 1929–30	1930–31 to 1934–35
1	United States	42,601	34,657	15,268	13,343	56.22	51.67
2	India	26,192	23,625	4,724	4,029	17.39	15.60
3	China	5,563	6,451	2,552	2,730	9.40	10.57
4	U.S.S.R.	2,017	4,883	1,021	1,775	3.76	6.87
5	Egypt	1,828	1,743	1,587	1,481	5.84	5.74
6	Brazil	1,492	2,457	504	772	1.86	2.99
7	Peru	305	328	246	274	0.91	1.06
8	Uganda	615	991	131	206	0.48	0.80
9	Mexico	472	349	253	195	0.93	0.76
10	Argentina	241	436	115	191	0.42	0.74
11	Anglo-Egyptian Sudan	270	349	126	160	0.46	0.62
12	Chosen*	495	448	138	132	0.51	0.51
13	All others	2,489	2,911	493	532	1.82	2.07
	Estimated world total	84,580	79,628	27,158	25,820	100.00	100.00

* Includes Manchuria.

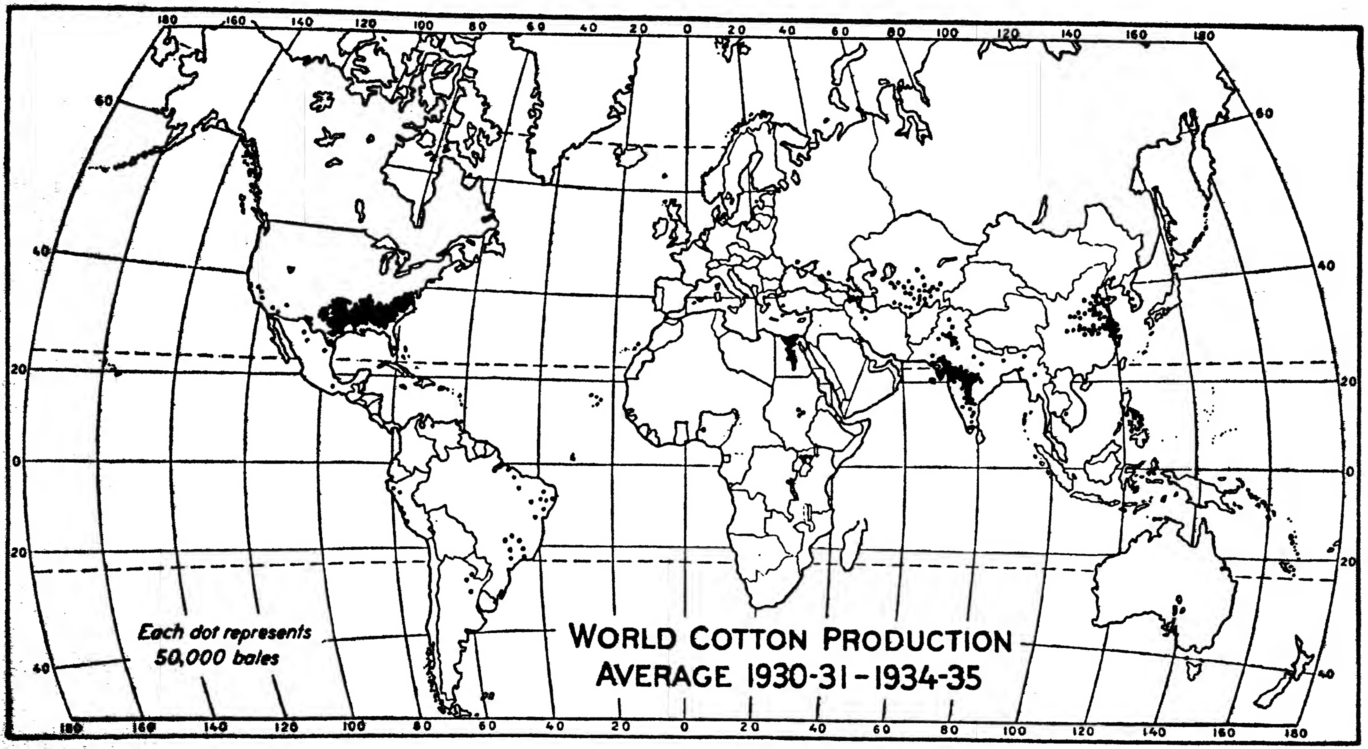


FIG. 93. World distribution of cotton production. Each dot represents 50,000 bales. (U. S. Dept. Agr. Bur. Agr. Econ.)

The distribution of cotton in the United States will be discussed under a separate heading. It will be observed from Table 54 that disrupted world economic conditions and the institution of cotton control programs in this country had definite effects on cotton distribution. The preeminent position of the United States as a world producer of cotton, however, remains unchallenged even though production for the second five-year period, 1930–31 to 1934–35, dropped from 56.22 to 51.67 per cent of total world production. The acreage of cotton relinquished by the United States was taken up by Russia, Brazil, Uganda, Argentina, the Anglo-Egyptian Sudan, and other countries.

India for many years has been surpassed only by the United States in the production of cotton. According to Bergsmark (3), the greater part of the Indian cotton is grown on the rolling uplands of Deccan. Cotton production attains its highest intensity on the Black Earth Belt of peninsular India. The soils here are fertile and have good moisture-retaining properties. The importance of this area as a cotton producer has been a major factor in making Bombay, a center located to the south, west, and northwest of this region, the principal cotton manufacturing city of India. Stine and Baker point out that, while the production of cotton in India — as in the Cotton Belt of the United States — is more concentrated in certain areas than in others, the crop is grown in nearly all parts of the country except in regions of very heavy rainfall as on the Burma coast, in the swampy Ganges lowlands of eastern Bengal, on the mountainous Malabar coast, and in the desert region of western Rajputana. The highest grade of Indian cotton, according to Finch and Baker (8), is produced in southern Madras near Tinnevelly, Madura, and Coimbatore. In this region the maximum rainfall comes between June and October, the annual amount being only 27 to 30 inches. The period of extreme drought occurs in March.

Rainfall in the cotton as well as in the cereal producing regions of India is extremely variable. Years of plenty are followed by years of dearth, and drought frequently injures the crop. Considerable progress has, however, been made in irrigation developments to remedy this situation. In the dry areas much of the cotton grown is of short-staple varieties.

Indian cotton is produced at great expenditures of labor on small

private land holdings. A high percentage of the crop is exported to Japan and China. Owing to the generally poor quality of the Indian crop, European importers prefer American to Indian cotton. India imports a small quantity of raw cotton, mostly American (see Table 56), and a large quantity of manufactured cotton goods, chiefly from England.

The future development of India's cotton industry depends mainly upon the production of more lint per acre and improvements in the crop produced rather than upon the expansion of cotton acreage.

China has grown cotton since the twelfth century. According to Cressey (5), the cultivation of cotton spread into China from central Asia by way of Kansu and Shensi. At present cotton is extensively grown in the valley of the Wei Ho near Sian (Sianfu). Other important areas are Shansi and Honan and the valley of the Yangtse River. The tensile strength of Chinese cotton is good, but the staple is coarse and short. The position of China in the international trade of cotton is summarized by Cressey in the following paragraph.

> "Although China is an exporter of cotton, she is also an importer, buying about twice as much as she sells. This peculiar situation is due to the fact that China produces short-staple cotton which Japan and the United States purchase for mixing with long-staple cotton and for special purposes, such as making blankets. The cotton which China buys is mostly of the long-fiber variety necessary for the manufacture of certain cloths. As China increasingly weaves her own cloth, the export of raw cotton will decline."

The cotton crop of the Union of Soviet Socialist Republics is produced in Turkestan and Transcaucasia. Cotton is grown farther north in the first of these regions than elsewhere in the world. The climate of the Russian areas is of the arid continental type, characterized by hot summers and cool winters. The increase in Russian cotton production is accounted for by recent irrigation developments and economic pressure aimed at self-sufficiency.

Egypt is the world's chief source of long-staple cotton. According to Norris (18), approximately one-third of the average crop of 1,500,000 bales is of a staple length of $1\frac{1}{4}$ inches and over, and the staple of the remainder of the crop, known as Uppers, ranges from $1\frac{1}{16}$ to $1\frac{3}{16}$ inches. Less than a century ago Egypt produced little

cotton. The Civil War in the United States greatly stimulated Egyptian production. After the close of that war, Egypt not only held its place gained as a world producer of high-quality cotton but continued to increase its production. At the present time cotton is the leading cash crop and the chief item of export.

Cotton, like all the other crops of the country, is grown under irrigation. Agriculture is confined to the delta, Lower Egypt, and the narrow valley of the Nile, Middle and Upper Egypt. The increased importance of cotton production during the past century is accounted for by the world demand for the high-quality cotton grown and by the great improvements made in irrigation facilities and practices. The oldest type of irrigation was of the flood or basin type. It is still common in Upper Egypt, but much of Middle and all of Lower Egypt is now under canal irrigation. While the flood type of irrigation led to the annual "renewal" of the soil by the silt deposited over the flooded areas, canal irrigation resulted in better water control and in the intensification of production.

Brazil has possibilities as a producer of cotton. Certain natural limitations must, however, be considered. The coastal region is rather wet and the interior is subject to droughts.

Most of the cotton of Peru is grown under irrigation in the alluvial bottoms of the coastal valleys. Both "smooth" and "rough" Peruvian cotton is produced. The latter is crinkly, brownish in color, and can for that reason be mixed successfully with wool in the production of expensive fabrics.

Distribution in the United States. The climatic conditions prevailing over the American Cotton Belt and their effects on the cotton crop have already been discussed. The effects of temperature and moisture conditions on the limits of cotton production are apparent from the cartographical view of cotton distribution in Fig. 94. The northern limits of cotton production are rather well defined by prevailing summer temperatures, while the western limits are determined quite definitely by the 23-inch annual precipitation line. Very little cotton is grown along the Gulf coast east of Galveston, and practically none in southern Florida. This is due in part to the greater autumn rainfall in these areas and in part to the swampy and in places sandy soils in this section. Production along the Atlantic coast is also not intense; poor soil conditions interfere with the proper development of the crop.

Throughout the entire Cotton Belt certain areas of concentration are evident. These are determined primarily by favorable soil conditions within this broad belt. Such areas of concentration are found in the Piedmont Plateau, the Upper Coastal Plain, the Black Prairie of Alabama and Mississippi, the bottom lands along the Mississippi River and Mississippi-Arkansas and Red River Deltas, the Black Waxy Prairies of Texas, and on the plains of western Oklahoma and the lower portion of the panhandle of Texas.

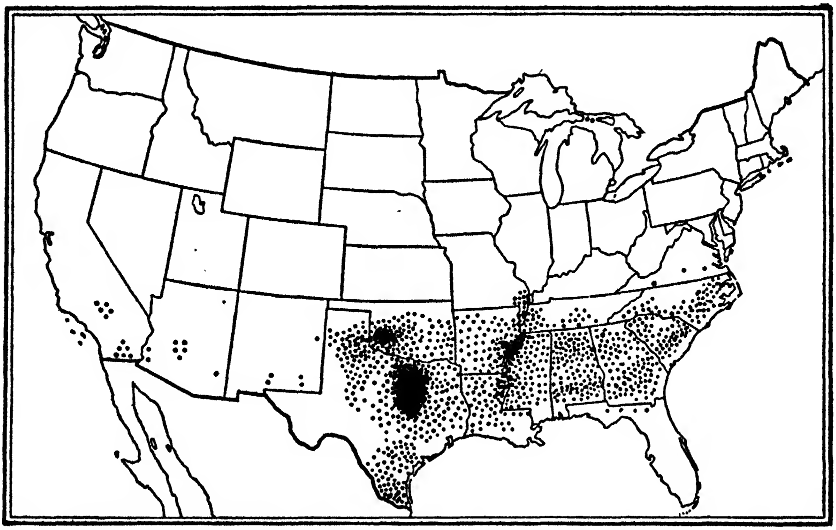


Fig. 94. Distribution of cotton production in the United States. Averages for the ten-year period 1928–1937. Each dot represents 25,000 acres.

Table 55 gives the cotton statistics of the United States by states. Cotton is an old crop in the eastern and central portions of the Cotton Belt. Its production on the dry plains of Oklahoma and Texas is comparatively recent. These western areas have received much of the blame of overproduction of cotton during recent years. The lower yields of Texas and Oklahoma are to a large degree accounted for by the lower rainfall prevailing in these areas as compared with the areas to the east. Furthermore, the lint produced is not as long as for the cotton produced on the fertile soils in the more humid areas. Nevertheless, cotton not only has established itself in these drier areas but is economically well entrenched. Even though yields are lower and the staple somewhat shorter than in the areas to the east, the costs of production are also lower. The

lower costs are accounted for in part by the more progressive and extensive methods of production, greater fertility of soil necessitating smaller outlay for fertilizer, and also by the fact that owing to the lower precipitation weeds are easily controlled. In much of this area stands are more readily obtained than in humid sections. Consequently, "cell-drop planting" is used. This gives the grower an opportunity to space his plants without the expense of chopping, that is, thinning down to the desired stand. The high summer temperatures are also effective in reducing and in places eliminating weevil damage.

TABLE 55. COTTON: ACREAGE HARVESTED, YIELD PER ACRE, PRODUCTION OF LINT — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGE AND PRODUCTION EXPRESSED IN THOUSANDS. GROSS WEIGHT OF BALES IS 500 POUNDS

Rank	*States*	*Acreage Harvested*	*Yield per Acre, in Lbs.*	*Production*		
				Average 1928–1937, in Bales	Percentage of U. S. Total	1938, in Bales
1	Texas	13,395	147	4,077	29.54	3,086
2	Mississippi . . .	3,436	225	1,596	11.57	1,704
3	Arkansas	2,903	212	1,273	9.22	1,349
4	Alabama	2,857	205	1,203	8.72	1,081
5	Georgia	2,721	212	1,192	8.64	852
6	Oklahoma . . .	3,098	133	876	6.35	563
7	South Carolina . .	1,652	243	827	5.99	648
8	Louisiana	1,596	214	711	5.15	676
9	North Carolina . .	1,219	281	702	5.09	388
10	Tennessee	945	238	466	3.38	490
	Other states . . .	1,162	—	877	6.35	1,106
	Total U. S. . . .	34,984	190.8	13,800	100.00	11,943

Cotton production in Arizona and California is limited to the southern irrigated valleys of these states. It will be observed from Table 55 that ten states of the Cotton Belt account for practically 94 per cent of the cotton produced in the United States. The remaining 6 per cent is grown in Missouri, California, Arizona, Florida, and Virginia.

Table 56 shows the exports of cotton from the United States to specified countries. Not all the cotton consigned to a given country may necessarily be consumed there; some of it may be consigned to agents at ports, notably Bremen, and hence classified as exports

to Germany rather than to the country where the cotton is actually consumed or used in the manufacture of goods to be reexported. Table 56 shows why the cotton industry is so vitally interested in the economic and political affairs of the four corners of the world.

TABLE 56. EXPORTS OF UNMANUFACTURED COTTON LINT FROM THE UNITED STATES TO SPECIFIED COUNTRIES. AVERAGES FOR THE FIVE-YEAR PERIOD OF 1929–30 TO 1933–34

Rank	*Country to Which Exported*	*Amount, in 1,000 Bales*	*Percentage of Total United States Export*
1	Germany	1,707	21.26
2	Japan	1,695	21.11
3	United Kingdom	1,332	16.59
4	France	805	10.03
5	Italy	686	8.54
6	China	497	6.19
7	Spain	306	3.81
8	Canada	185	2.30
9	Belgium	160	1.99
10	Netherlands	141	1.76
11	British India	92	1.15
12	Sweden	63	0.78
13	Portugal	61	0.76
14	U.S.S.R.	58	0.72

FIBER FLAX

Historical. Until comparatively recent times the nations of western Europe depended for their textiles chiefly on wool and flax. Cotton has long been used by the people of eastern Asia. Marco Polo, the Venetian traveler who visited nearly all the countries of Asia in the thirteenth century, found that cotton was then being spun and woven in certain districts in China. Columbus found the red men in America spinning and weaving cotton. But through the centuries of Ancient Egypt, Greece, and Rome, through the long Middle Ages, and well up into modern times, the use of cotton fiber was confined chiefly to the peoples in the countries of its early production. It was not until English inventive genius was applied to the creation of modern cotton manufacturing machinery and American genius to the creation of the gin that cotton began to be extensively used in Western civilizations. As cotton and cotton goods gained in popularity, fiber flax and linen

possessions. The plants are exceedingly drought-resistant. The United States imports sisal for the making of binder twine, most of the supply coming from Mexico and the Dutch East Indies.

REFERENCES

1. Agelasto, A. M., C. B. Doyle, G. S. Meloy, and O. C. Stine, "The cotton situation," *U. S. Dept. Agr. Yearbook* 1921:323–406.
2. Baker, O. E., "Agricultural regions of North America, Part II, The South," *Econ. Geog.*, 3:50–86 (1927).
3. Bergsmark, D. R., *Economic Geography of Asia.* Prentice-Hall, New York, 1936.
4. Brown, H. B., "A brief discussion of the history of cotton, its culture, breeding, harvesting, and uses," *La. State Dept. Agr. and Immigr.*, 1939.
5. Cressey, G. B., *China's Geographic Foundations.* McGraw-Hill, New York, 1934.
6. Dowell, A. A., and O. B. Jesness, *The American Farmer and the Export Market.* University of Minnesota Press, Minneapolis, 1934.
7. Ewing, E. C., "A study of certain environmental factors and varietal differences influencing the fruiting of cotton," *Miss. Agr. Exp. Sta. Tech. Bull.* 8, 1918.
8. Finch, V. C., and O. E. Baker, *Geography of the World's Agriculture.* Govt. Printing Office, Washington, 1917.
9. Garside, A. H., *Cotton Goes to Market.* Stokes, New York, 1935.
10. Henderson, W. O., *The Lancashire Cotton Famine*, 1861–1865. Manchester University Press, Manchester, 1934.
11. Hill, A. F., *Economic Botany.* McGraw-Hill, New York, 1937.
12. Huntington, E., F. E. Williams, and S. von Valkenburg, *Economic and Social Geography.* Wiley, New York, 1933.
13. Hutcheson, T. B., T. K. Wolfe, and M. S. Kipps, *The Production of Field Crops.* McGraw-Hill, New York, 1936.
14. Klages, K. H. W., "Spacing in relation to the development of the flax plant," *Jour. Amer. Soc. Agron.*, 24:1–17 (1932).
15. Marbury, J. R., "Relation of weather conditions to growth and development of cotton," *U. S. Dept. Agr. Yearbook* 1904:141–150.
16. Marquart, B., *Der Hanfbau.* Paul Parey, Berlin, 1919.
17. Morgan, M. F., J. H. Gourley, and J. K. Ableiter, "The soil requirements of economic plants," *U. S. Dept. Agr. Yearbook* 1938:753–776.
18. Norris, P. K., "Cotton production in Egypt," *U. S. Dept. Agr. Tech. Bull.* 451, 1934.
19. Robinson, B. B., "Flax-fiber production," *U. S. Dept. Agr. Farmers' Bull.* 1728, 1940.

20. Smith, G. R., "Gin damage of cotton in relation to rainfall," *N. C. Agr. Exp. Sta. Bull.* 306, 1936.
21. Stine, O. C., and O. E. Baker, *Atlas of American Agriculture*, Part V, Sec. A, Cotton. Govt. Printing Office, Washington, 1918.
22. Vance, R. B., *Human Factors in Cotton Culture.* University of North Carolina Press, Chapel Hill, 1929.
23. Ware, J. O., "Plant breeding and the cotton industry," *U. S. Dept. Agr. Yearbook* 1936:657–744.

Chapter XXIX

ANNUAL LEGUMINOUS FORAGE CROPS

INTRODUCTION

Annual legumes are utilized for a variety of purposes. The use of annual legumes for human consumption was discussed in Chapter XXIV under the heading, "Edible Legumes." Certain legumes, as soybeans and peanuts, are grown not only for human consumption but also for forage and for the production of vegetable oil. Others are grown strictly for forage and soil improvement purposes depending on their specific characteristics. Climatic as well as economic conditions determine to a high degree the special uses made of certain annual legumes.

SOYBEANS

(*Soja max*)

The soybean, while being used in the United States primarily as a forage crop, is of considerable importance as a producer of vegetable oil. For that reason this crop was discussed in Chapter XXVII, "Oil Producing Crops."

COWPEAS

(*Vigna sinensis*)

Historical. The cowpea in reality is not a pea but a bean. It was commonly cultivated for human food in the Old World before the discovery of America. According to Piper (16), "it is without doubt the *Phaseolus* of Pliny, Columella and other Roman writers, but this name became applied also to the kidney-bean following its introduction into Europe from America." In Italy the blackeye cowpea is still called by the same name as kidney beans, *fagiola*, which is the Italian equivalent of Phaseolus.

The cowpea is a native of central Africa. Wild plants differing but little from cultivated cowpeas occur throughout much of that

continent. According to Morse (14), "the large number and great diversity of cultivated varieties throughout Africa and over the southern half of Asia and the adjacent islands as well as the Mediterranean region of Europe indicate that the cowpea is of ancient cultivation for human food."

The cowpea was grown in North Carolina in 1714, coming in all probability from the West Indies where it was early introduced by the Spaniards. The first culture of the crop in Virginia was reported about 1775.

Utilization. The cowpea is generally regarded as a forage and soil-improvement crop, though the Blackeye and White varieties are commonly used for human food in the southern states. Thus Morse (13) in speaking of conditions prevailing in the southern states brings out that "the cowpea has been used more as a soil renovator than any other legume because it is so easily grown, has such a marked effect upon succeeding crops, and succeeds under such a great diversity of conditions."

Climatic and Soil Relationships. The temperature requirements of the cowpea reflect the tropical origin of the crop. The crop demands higher temperatures than corn. This is well illustrated in Fig. 95, taken from Morse (14), showing the comparative distribution of cowpeas in the United States. The crop has greatest value in the southern states and becomes of decreasing importance in the North. Cowpeas require higher temperatures than early maturing varieties of soybeans. The leaves of cowpeas are readily damaged by late spring and early fall frosts.

After cowpeas are once established, they are able to withstand relatively dry conditions. Droughts, however, reduce both hay and especially seed yields. This is also indicated in Fig. 95. The importance of cowpeas tapers off rapidly as the southern Great Plains area is approached.

Cowpeas can be successfully grown under a great variety of soil conditions, the only specific demand being that the soil be well drained. They do well on sandy and also on heavy clay soils, and better than clover or alfalfa on thin soils or on soils that are low in lime. "No other legume," states Morse (14), "can be grown so successfully on such a variety of soils under adverse conditions as the cowpea." Cowpeas are quite similar with respect to tolerance to adverse soil conditions to the annual lespedezas. The ability

of the crop to grow on poor soils together with its great value as a soil-improving crop accounts in part for the great importance of cowpeas in the southern states. Where the crop is to be used for the production of seed, better results are obtained on soils of moderate than on those of high fertility. A high fertility level leads to an abundant vine growth to the detriment of seed development.

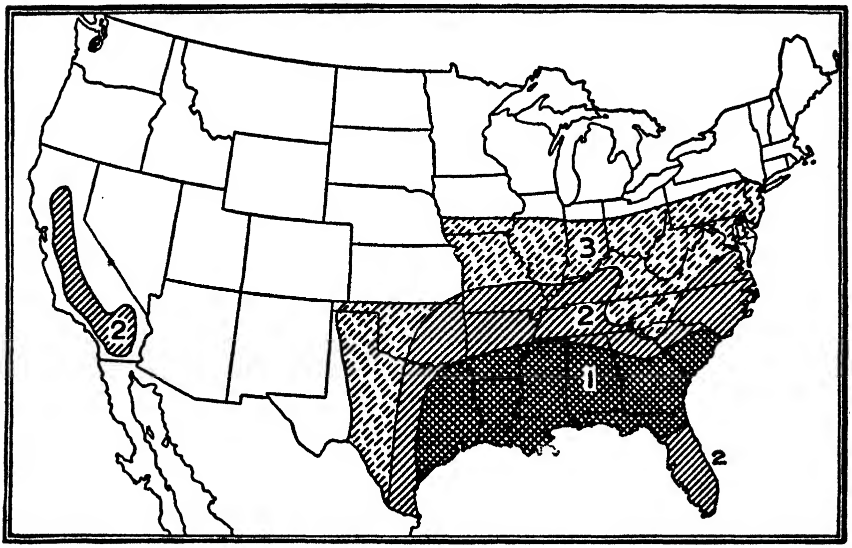


FIG. 95. Outline map of the United States showing the comparative distribution of cowpeas. (1) Area in which cowpeas are grown most extensively; (2) area in which cowpeas are grown quite generally; (3) area in which cowpeas are grown to some extent. (After Morse, 14.)

Distribution. No data on the world distribution of cowpeas are available. It is known, however, that the crop is of considerable importance in Asia and particularly in India. Cowpeas are also grown in the Mediterranean region. In these areas the crop is grown largely for seed and for human consumption. Only the Blackeye and White varieties are used for human consumption in the United States. Their production is of great importance in the Cotton Belt and in the interior valleys of California. The California Agricultural Experiment Station has developed a wilt-resistant Blackeye "pea" that gives promise in the seed producing areas of that state.

The important cowpea producing states together with the acreage in 1936 expressed in 1,000 acres are: Texas, 998; South Carolina, 803; Georgia, 625; Arkansas, 517; Mississippi, 423; Alabama, 396; North Carolina, 290; Louisiana, 216; Illinois, 181; and Tennessee, 163. These tabulated acreages comprise the areas where the crop is grown alone plus approximately one-half the interplanted acres.

ANNUAL LESPEDEZAS

Varieties and Origin. Since the range of adaptation of the annual lespedezas is definitely associated with their specific characteristics, it is necessary to call attention to the characteristics of the several species and varieties. The subdivision of the genus *Lespedeza* and the enumeration of the most important varieties are given by Pieters (15) in the following paragraph.

> "The genus *Lespedeza* includes some 125 species of which only 2 are annuals. Both of these species *L. striata* (Thunb.) H. & A. and *L. stipulacea* Maxim. have been introduced into the United States from the Orient. *L. striata* has been in this country for about 100 years while *L. stipulacea* was introduced from Chosen (Korea) in 1919. Named varieties of each species are now more or less widely distributed. Under *L. striata* are to be distinguished the common lespedeza, Kobe, and Tennessee 76, and under *L. stipulacea* are Korean, Harbin, and the early Korean U.S.D.A. 19604."

The term "common lespedeza" has been used synonymously with *Lespedeza striata*. Pieters recommends that the term "common lespedeza" be used to designate unselected forms of this species growing spontaneously throughout its range as distinguished from selected varieties such as Tennessee 76 and Kobe. Likewise the term "Korean" should be used to designate the unselected forms of *L. stipulacea;* selected forms can then be designated by special names.

Common lespedeza is a slender plant, usually prostrate in growth except in dense stands, and has small leaflets and purple flowers. Kobe is larger, coarser, and somewhat more erect and has larger leaves and distinctly larger seeds.

Lespedeza stipulacea differs from *L. striata* in having significantly broader leaflets and stipules.

Utilization. The annual lespedezas are used strictly for forage and soil-improvement purposes. Their ability to grow on poor and

even acid soils makes them of special value for soil conservation and soil improvement.

The ravages of clover anthracnose (*Colletotrichum trifolii*) have resulted in marked decreases in the acreages of red clover in Tennessee, Kentucky, and adjacent states; that is, in areas to which lespedeza is well adapted. As a result large acreages formerly devoted to red clover production are now used for the growing of lespedeza. The availability of anthracnose-resistant strains of red clover may be expected to counteract this trend to some extent. But the fact remains that lespedeza is more dependable than either red clover or alfalfa in this area. This dependability of the crop even under adverse soil conditions has, according to Kinney *et al.* (5), contributed much to its popularity. Owing to the tolerance of lespedezas for soil acidity, the liming of acid soils is not as essential in the production of leguminous feeds when they are used as when clovers or alfalfa are grown for the purpose.

Lespedeza as a forage is used especially for the production of pasturage. While the plant is an annual, it will maintain itself over a period of years under proper pasture management. Under favorable climatic conditions the crop is a prolific seed producer. The larger growing lespedezas, such as Korean and Tennessee 76, are also valuable hay crops, especially where soil and other conditions interfere with the production of red clover and alfalfa. The production of lespedeza hay is, however, more or less limited to fairly productive soils.

Geographical Range. Some varieties of lespedeza will produce seed from the Gulf of Mexico to the northern border of Illinois. Harbin will, according to Pieters, produce seed to the northern limits of the United States. Lespedeza is, however, in a poor competitive position to replace the ordinary clovers to any appreciable extent in the northern areas of the United States. Lespedezas are hot-weather and short day plants, most of them will not bloom and seed under long day conditions. The slow growth of the plants during the spring months also interferes with the utilization of lespedeza in northern areas.

"Lespedezas," states Pieters, "are strongly drought-resistant, but during prolonged drought little if any growth is made." This reaction to moisture conditions sets a rather definite limit to the western distribution of the crop. The lespedezas cease to be a crop

of importance farther west than the eastern tier of counties in Kansas and Oklahoma.

The varieties of *Lespedeza striata* are best suited to the area from northern Tennessee to the Gulf. Kobe and Tennessee 76 are late-maturing varieties. The range of Kobe extends from southern Illinois to southern Mississippi and from eastern North Carolina to western Tennessee. Tennessee 76 is chiefly grown in eastern and central North Carolina and in western Tennessee. *Lespedeza stipulacea* (Korean) matures earlier than *L. striata.* It reaches its best development in a zone including Virginia and North Carolina on the east and eastern Kansas and Oklahoma on the west. Korean lespedeza is also suited to the Piedmont area of South Carolina, Georgia, Alabama and extends north to central Illinois and Indiana.

CRIMSON CLOVER

(*Trifolium incarnatum*)

Historical. Crimson clover is a native of Europe. It has long been grown as a forage and soil-improvement crop in the countries of western and central Europe. The crop was introduced into the United States as early as 1818, and seed was widely distributed by the Patent Office in 1855. On account of the showy, bright-crimson heads the plant was first regarded more for its ornamental value than as a forage plant. It was not until about 1880 that the value of the crop for agricultural purposes began to be appreciated (Kephart, 4).

Utilization and Distribution. Crimson clover is an important winter annual legume and is used for the production of spring and early summer pasture, as a cover and green manure crop, and to some extent for hay. The crop is often seeded for the production of hay in combination with rye, vetch, and Italian ryegrass. Crimson clover is frequently seeded in corn and cotton at the last cultivation of those crops.

Crimson clover is quite tolerant in its soil requirements. It does well on sandy soils. It is not as dependent on lime as red clover and alfalfa, being more like alsike clover in that respect. The crop does not, however, thrive on very acid soils. Furthermore, good drainage is required.

Crimson clover is adapted to cool, humid areas. It can be used

as a winter annual only where temperatures are not severe or too variable. Ordinarily it does not survive the winters in latitudes north of southern Pennsylvania. The crop matures prior to the advent of high summer temperatures. Dry conditions in the autumn months sometimes interfere with the establishment of stands. Crimson clover can be grown as a summer crop in northern areas, but other clovers may be expected to give better returns in such sections.

Figure 96, taken from Hollowell (2), gives the location of the principal crimson clover producing areas of the United States.

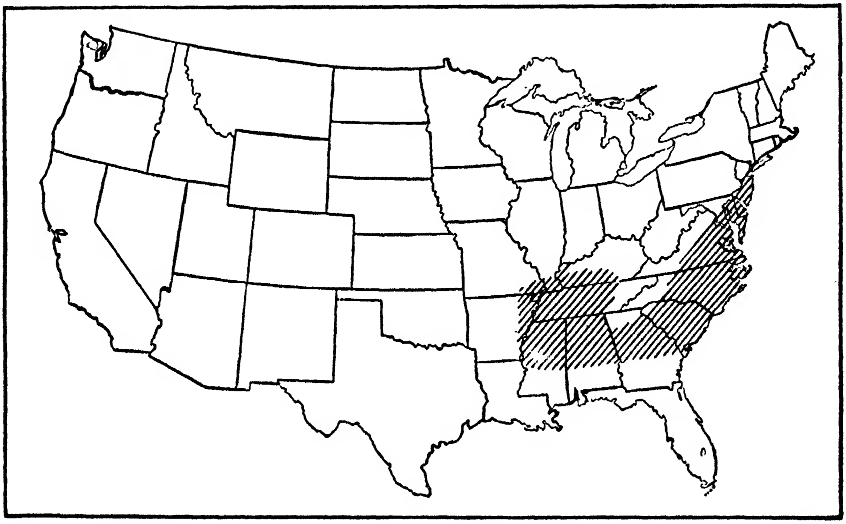


Fig. 96. Principal crimson clover producing regions of the United States. (After Hollowell.)

It will be observed that the crop is grown along the Atlantic Coastal Plain and the more humid portions of the Cotton Belt. Crimson clover is also adapted to the western portions of Oregon and Washington, but it has not become of importance there. Other leguminous plants in this area are generally more productive than crimson clover.

BUR CLOVER

Species of Bur Clover. Two important species of bur clover are commonly grown in the United States, namely, the spotted or southern bur clover (*Medicago arabica*) and the toothed or California

bur clover (*M. hispida*). Two other species are grown to a limited extent, the Tifton bur clover (*M. rigida*) and *M. minima*. The Tifton bur clover has been grown and distributed from the Georgia Coastal Plains Experiment Station, located at Tifton, while the *M. minima* has been naturally introduced in a number of places in the southern states and is gradually spreading. According to McKee (9), *M. minima* is comparable with spotted bur clover in winter-hardiness, but Tifton bur clover is the most hardy of all and usually will survive most winters as far north as Washington, D. C.

Several species of spotted bur clovers with spineless pods, as the button clover (*M. orbicularis*), snail clover (*M. scutellata*), and tubercled clover (*M. tuberculata*), have been tested. "Experience has shown, however, that the varieties with large spineless burs cannot be maintained in pastures except when given special attention and protection. . . . The seed of spineless varieties with small burs," continues McKee (9), "escape grazing animals more readily, and consequently are more persistent and are not uncommon in California."

Utilization. The bur clovers are winter annuals; that is, they germinate in the autumn, grow during the fall, winter, and early spring, and mature early in summer. Because they are prolific seed producers, and also because of the procumbent habits of growth of the plants and the fact that the burs are protected to some extent by spines, the plants volunteer readily. Under proper systems of management the plants may maintain themselves indefinitely. Sheep are fond of the burs and eat them readily, especially after they have been softened by rain.

Bur clover is utilized mostly as pasture for cattle, hogs, and sheep. It is reported that horses will eat the toothed or California bur clover but will avoid the spotted bur clover. Bur clover is also used to advantage in combination with bermuda grass in permanent pastures. The bermuda provides pasturage during the summer months, whereas the bur clover begins to grow with cool weather in fall and provides pasturage during the winter and spring. Bur clover may be pastured in North Carolina by the middle of February, and near the Gulf it furnishes practically continuous winter pasturage.

Under favorable conditions bur clover can be used for the produc-

tion of hay. However, if the crop is to be used for that purpose it is best to seed it in mixtures with either winter oats or wheat. The cereals will tend to support the bur clover.

Bur clover is also used to advantage as a cover and green manure crop. The habit of the plants to volunteer enhances their value for this purpose.

Geographical Range. The bur clovers are of value only in areas where the winters are mild and where moisture is available during the winter and early spring months. They are extensively grown in the Mediterranean area and also in Australia, Argentina, and Chile.

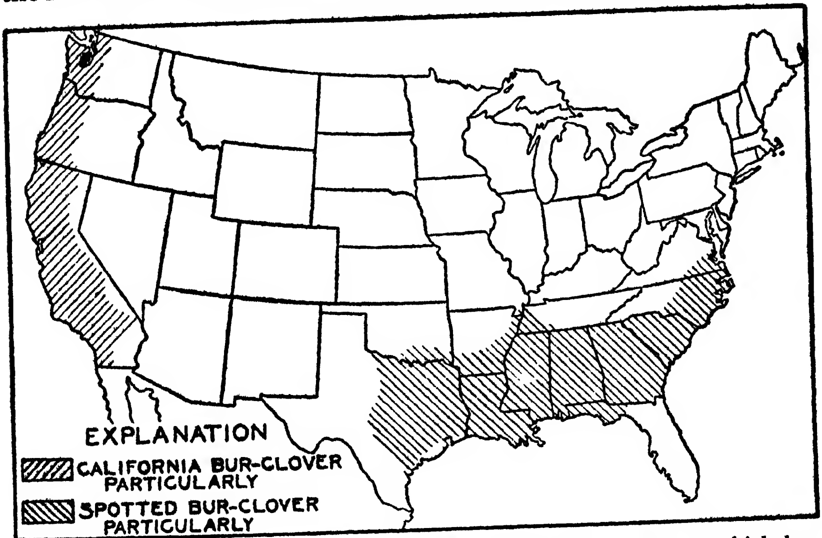


FIG. 97. Outline map of the United States, showing the regions to which bur clover is adapted. (After McKee.)

In the United States bur clover is grown in the Cotton Belt and along the Pacific coast from California to western Oregon and Washington. On account of temperature limitation the bur clover producing regions of the South do not extend quite as far to the north as those producing cotton. The crop is very important in the lower ranges of California but only of limited importance in Oregon and Washington. Spotted bur clover is better adapted to conditions in the Cotton Belt and especially to the northern portion of the bur clover producing area than the toothed or California bur clover. McKee (9) reports that California bur clover is destroyed in winter by temperatures that do little or no harm to

the spotted bur clover. Both the toothed and the spotted bur clovers are grown in California.

Figure 97, taken from McKee (9), shows the regions of the United States to which bur clover is adapted.

VETCHES

Species and Varieties. Plants of the genus *Vicia* are commonly referred to as vetch. One of the exceptions to this is the horsebean or broadbean (*Vicia faba*). This species is grown primarily for seed; it is therefore classified as an edible legume.

The vetches of most importance as listed by McKee and Schoth (12) are common vetch (*Vicia sativa*), hairy vetch (*V. villosa*), smooth vetch (*V. villosa*), purple vetch (*V. atropurpurea*), narrowleaf vetch (*V. angustifolia*), woollypod vetch (*V. dasycarpa*), bitter vetch (*V. Ervilia*), monantha vetch (*V. monantha*), Hungarian vetch (*V. pannonica*), and Bard vetch (*V. calcarata*). With the exception of bitter vetch, which is grown in the Mediterranean area, these species are all used in the United States.

The common agricultural species are all viny or weak-stemmed. The stems attain a length of from two to five feet or more and unless supported by companion crops assume a procumbent position. While some of the different species have quite distinctive characteristics, others are very much alike and sometimes are almost indistinguishable. The various species show great variations with regard to climatic adaptation, and some differences in regard to soil tolerances.

Utilization. All of the commercial vetches make good hay, silage, and pasturage. Since they grow or at least maintain themselves during the winter months, they are also of value as cover and green manure crops. Their ability to grow at moderate temperatures and their rapid development in spring make them of value as soiling crops. Surplus and waste seed is used in ground poultry feeds.

Common and Hungarian vetch are most generally used for hay. For that purpose they are commonly grown with a companion crop such as winter oats. Narrowleaf vetch may be sown to advantage in Johnson grass-infested bottom lands in the South.

Probably the greatest use of vetch is for green-manuring. Hairy vetch and smooth vetch are used extensively as cover and green

manure crops in the Cotton Belt. Monantha vetch is used for the same purpose in the extreme South, and purple vetch is used for green manure in California. Owing to their tendencies to volunteer and create objectionable admixtures, the winter-hardy hairy vetch and smooth vetch should not be grown in strictly winter wheat producing areas.

Seed Production. Most of the seed of common, Hungarian, purple, and monantha vetches are produced in the United States. Western Oregon and western Washington produce most of the vetch seed of the country. Hairy vetch is also produced in Europe in the countries bordering the Baltic Sea and south to Hungary, while the less winter-hardy common vetch is produced in the more southern European countries and in the British Isles. Bitter vetch is produced in the eastern Mediterranean region where it is used as stock feed.

The vetch seed producing areas of the United States are enumerated by McKee and Schoth in the following paragraph.

> "In the United States hairy-vetch seed is produced in Michigan, western Oregon, and western Washington; common and Hungarian in western Oregon, and western Washington; monantha and purple in western Oregon, western Washington, and northwestern California; smooth in western North Carolina; and woollypod vetch in western Oregon."

Distribution. The distribution of the many species of vetch is closely related to the abilities of the different types to endure winter temperatures. Hairy vetch is winter-hardy and is for that reason extensively grown in northern Europe and in the northern portion of the United States. The smooth vetch is reported by McKee and Schoth to be winter-hardy but somewhat less so than hairy vetch. In turn the woollypod vetch is reported by these same investigators to be somewhat less hardy than the smooth vetch. Klages (6) tested the winter-hardiness of the various vetches mentioned in this discussion, with the exception of smooth vetch, at the Oklahoma Agricultural Experiment Station. All types except hairy vetch, woollypod vetch, and Hungarian vetch were not sufficiently winter-hardy to survive under northern Cotton Belt conditions. The first two showed no winter injury; the Hungarian vetch showed 14 per cent of winterkilling; all of the other species were entirely killed during the more severe of the two years of the test. The non-

winter-hardy species are limited to regions with mild winters, the Central and Southern Cotton Belt, and the western portions of the Pacific states. Hairy vetch is the only variety recommended for fall planting in the North.

The vetches are quite similar to peas with regard to their moisture and temperature requirements during the growing season in that they demand moderate temperatures and moisture supplies. None of the vetches are particularly drought-resistant.

Vetches are rather tolerant with regard to their soil requirements. They are less affected by acid soil conditions than most legumes. The soil response of the various species differ. Thus hairy, smooth, and monantha vetches do well on poor sandy soils, while Hungarian vetch succeeds on wet soils where other kinds produce but little growth.

OTHER ANNUAL LEGUMINOUS PLANTS

Austrian Winter Pea (*Pisum sativum*). The Austrian winter pea is the most winter-hardy of the field pea varieties. On account of its low minimum-temperature growing point it is highly valued as a winter cover and green manure crop. Next to hairy vetch it is the most widely used winter legume in the United States. The Austrian winter pea is not as winter-hardy as hairy vetch. It will survive the winters only in the humid portions of the Cotton Belt. The crop is not commonly grown outside of the Cotton Belt. Some seed is produced from fall plantings in the Pacific Northwest, and a limited amount from spring seedings in the northern Great Plains area.

Velvetbean (*Stizolobium spp.*). This vigorous-growing plant produces vines, with the exception of the bush varieties, usually attaining a length of 10 to 25 or more feet. The crop is utilized as a pasture and hay crop and as a summer green manure crop. The ground beans are also used for feed. Since, however, the pods are generally picked by hand, harvesting costs run high.

The production of velvetbeans in the United States is found on the well-drained Coastal-Plains soils of the South Atlantic and Gulf states. The crop demands high summer temperatures and a fairly abundant supply of moisture. Up until 1906 the Florida velvetbean was the only species grown in the country. This is a late variety requiring eight or nine months to reach maturity. Since

that time, early-maturing varieties have been introduced from China and Japan. These early-maturing varieties can, according to Piper and Morse (17), be grown in the northern portion of the Cotton Belt. However, as far north as that they have no special advantage over cowpeas or soybeans.

Crotalaria (*Crotalaria spp.*). McKee and Enlow (11) report that the genus *Crotalaria* contains around 600 species. Only two, *Crotalaria striata* and *C. spectabilis*, are grown commercially in the United States. The crop demands a long growing season, high temperatures, and fairly abundant supplies of moisture. The principal use is for green manure. Crotalaria hay is reported to produce poisoning in cattle. Seeds are poisonous to swine and poultry. The crop does well on poor sandy soils in the South. Most of the seed used in the southern United States is imported from Puerto Rico. Some seed is grown in Florida.

Berseem (*Trifolium alexandrinum*). Berseem or Egyptian clover occupies an important role in the agriculture of Egypt, where it is the foundation of the dairy and beef stock industry. It is also used as a green manure crop.

Berseem resembles red clover in its habits of growth. The stems are hollow and very succulent. Most of the roots are found in the first two feet of the soil. The crop is tolerant of moderate quantities of white alkali. This annual legume will produce four to five crops of hay per year under favorable conditions.

Kennedy and Mackie (3) indicate that the crop promises to be of value as a leguminous crop for winter growing under irrigation in regions with a climate similar to that of the Imperial Valley of California. The crop is grown with success in Italy and Australia. In Australia it is referred to as "winter lucerne" because it amply fills in the period when alfalfa is dormant.

Subterranean Clover (*Trifolium subterraneum*). This annual clover is reported to be a native of Europe, Asia, and Africa. It is found especially in the Mediterranean regions and in central and southern Europe. It was introduced into Australia where it is now being used as a pasture crop. Harrington (1) considers it as a pasture legume of first importance in the temperate regions of southern and eastern Australia. Leidigh (8) regards the crop as valuable in southeastern Texas, but states that it is not especially drought-resistant. Klages (7) found that the plant's lack of ag-

gressiveness and drought resistance made it unsuitable in central Oklahoma.

Subterranean clover is quite similar to bur clover in its habits of growth but is probably less drought-resistant. The plants remain green farther into early summer than bur clover. The plants reseed themselves by burying a part of the seed pods in the ground much like peanuts. It is a prolific seed producer and under humid conditions will maintain itself year after year. Since subterranean clover is not especially winter-hardy, it can be used only in the central and southern portion of the Cotton Belt.

Common Sesbania (*Sesbania macrocarpa*). This annual upright-growing legume is native to North America and extends as far north as Alabama, Georgia, and Arkansas. Sesbania, as it is known in the trade, is used strictly for soil improvement. It is a subtropical, summer-growing plant, making but little growth in cool weather. Where moisture is available, it grows rapidly at high temperatures and under conditions of very low atmospheric humidity. Sesbania demands fertile soils. According to McKee (10), the crop is used for green manure in connection with the production of winter truck crops in the Imperial and Coachella Valleys of California and in the Yuma and Salt River Valleys of Arizona.

Sour Clover (*Melilotus indica*). Sour clover is an upright-growing winter annual with much the same temperature growth requirements as bur clover. It is used as a green manure crop in the Southwest, the lower Mississippi Delta, and on the black lands of Mississippi and Alabama.

Serradella (*Ornithopus sativus*). Serradella is a vetchlike annual native of the Iberian Peninsula and Morocco. It is cultivated as a forage and green manure crop in western and central Europe and is of special importance as a soil-improvement crop on the sandy soils along the North and Baltic Seas. It has not become of importance in the United States.

Lupine (*Lupinus spp.*). Lupines are used in the areas with sandy soils in western and central Europe, and especially in Germany, for soil-improvement purposes. They have not become established commercially in this country.

REFERENCES

1. Harrington, J. E., "Subterranean clover," *Jour. Dept. Agr. of Victoria*, 34:609–614 (1936).
2. Hollowell, E. A., "Crimson clover," *U. S. Dept. Agr. Leaflet* 160, 1938.
3. Kennedy, P. B., and W. W. Mackie, "Berseem or Egyptian clover," *Calif. Agr. Exp. Sta. Bull.* 389, 1925.
4. Kephart, L. W., "Growing crimson clover," *U. S. Dept. Agr. Farmers' Bull.* 1142, 1922.
5. Kinney, E. J., R. Kenney, and E. N. Fergus, "The lespedezas in Kentucky," *Ky. Agr. Exp. Sta. Circ.* 297, 1937.
6. Klages, K. H. W., "Comparative winterhardiness of species and varieties of vetches and peas in relation to their yielding ability," *Jour. Amer. Soc. Agron.*, 20:982–987 (1928).
7. ———, "Comparative ranges of adaptation of species of cultivated grasses and legumes in Oklahoma," *Jour. Amer. Soc. Agron.*, 21:201–223 (1929).
8. Leidigh, A. H., "Subterranean clover — a new sandy-land grazing crop for southeastern Texas," *Tex. Agr. Exp. Sta. Circ.* 37, 1925.
9. McKee, R., "Bur clover cultivation and utilization," *U. S. Dept. Agr. Farmers' Bull.* 1741, 1934.
10. ———, "Summer crops for green manure and soil improvement," *U. S. Dept. Agr. Farmers' Bull.* 1750, 1939.
11. ———, and C. R. Enlow, "Crotalaria, a new legume for the South," *U. S. Dept. Agr. Circ.* 137, 1931.
12. ———, and H. A. Schoth, "Vetch culture and uses," *U. S. Dept. Agr. Farmers' Bull.* 1740, 1934.
13. Morse, W. J., "Cowpeas: utilization," *U. S. Dept. Agr. Farmers' Bull.* 1153, 1920.
14. ———, "Cowpeas: culture and varieties," *U. S. Dept. Agr. Farmers' Bull.* 1148, 1924.
15. Pieters, A. J., "The annual lespedezas as forage and soil-conserving crops," *U. S. Dept. Agr. Circ.* 536, 1939.
16. Piper, C. V., *Forage Plants and Their Culture.* Macmillan, New York, 1937.
17. ———, and W. J. Morse, "The velvetbean" (revised by W. J. Morse), *U. S. Dept. of Agr. Farmers' Bull.* 1276, 1938.

Chapter XXX

BIENNIAL AND PERENNIAL LEGUMINOUS FORAGE CROPS

ALFALFA

(*Medicago sativa*)

Importance as a Forage Crop. Alfalfa is the most valuable hay crop produced in the United States. While it is not grown on as many farms in the country as timothy and clover, the total tonnage of alfalfa hay is greater than that produced by timothy and clover. In 1934, alfalfa acreages were reported on 877,453 farms; the total acreage amounted to 11,669,000 acres; and the total production of alfalfa hay was 18,742,100 tons. The corresponding data for timothy and clover, grown either alone or in mixtures, were 1,247,079 farms, 19,978,700 acres, and 16,346,100 tons of hay. All other tame and wild grasses were grown on 994,619 farms, on 17,930,813 acres, which produced 11,798,065 tons of hay. Furthermore, the importance of alfalfa as a hay crop has been increasing. As stated by Westover (16), in 1919 only one-eighth of the total hay acreage of the United States was in alfalfa; by 1938 the crop occupied over one-fifth of the total acreage. In 1938 alfalfa was grown on 13,462,000 acres in the country and produced 28,858,000 tons of hay. Data dealing with the comparative acreages and tonnages of alfalfa and other classes of hay do not bring out the full value of alfalfa as a forage crop. Alfalfa produces not only higher yields per acre than the other perennial forage crops but also has a higher feeding value per ton of hay produced. This is the case especially in comparisons of alfalfa with grass and legume-grass mixed hays. As a result of its ability to produce a high tonnage and a hay of exceptionally high quality, alfalfa supports a larger number of animal units than any other hay produced in the United States.

The forage uses of alfalfa are not limited to the production of hay. It has a high carrying capacity as a pasture crop. When

properly handled it produces a valuable silage. In addition to its energy content, alfalfa is a valuable source of carotene, riboflavin (vitamin G), protein, and calcium. Primarily because of its high content of these ingredients alfalfa is used not only as a general feed but also in special feeds such as the laying and growing rations for poultry.

Importance as a Soil Builder. In areas to which alfalfa is adapted it provides the cornerstone of systems of crop rotations designed to maintain or even to increase the fertility of the soil. In addition, its early and prolific growth makes it valuable in rotation systems for weed-control purposes, even for the control of troublesome perennial weeds.

Throckmorton and Salmon (15), in speaking of the merits of alfalfa, state that "there is no other crop which is so essential in relation to the live-stock industry, so useful to rotate with other crops, or so valuable in proportion to the cost of production."

Historical. Alfalfa is one of the oldest of plants cultivated solely for forage. *Media* or Persia is in all probability the region of its original cultivation. Wild alfalfas closely resembling the cultivated plants are found in this area. The ancient Persians used alfalfa extensively and carried the plant with them in their military expeditions. Thus the armed forces of Persia carried alfalfa to Greece. From there it reached northern Africa and thence found its way to Italy. Early Greek and Roman writers testified their high esteem for alfalfa, or *Medica* as they called it. Alfalfa was introduced into Spain by the Arabs. From there it moved into France, Germany, and England. It seems strange that a plant as valuable as alfalfa did not become of agricultural importance in western Europe until the seventeenth century. Lack of knowledge of the soil requirements of the plant, and failure to inoculate the soils on which the crop was first sown were no doubt contributing factors in the slow penetration of alfalfa into the humid area of western Europe. In this connection it should be kept in mind that alfalfa has for long periods been regarded as a crop adapted only to subhumid and relatively dry regions. Its production in temperate humid areas is of comparatively recent origin.

Alfalfa was carried to the western hemisphere by the Spaniards, probably first to Mexico and thence to South America. Gold seekers, on their way around Cape Horn, picked up seed of the

plant in Chile and brought it to California in the late forties or early fifties of the nineteenth century. From there it spread rapidly to the north and east. Earlier introductions of alfalfa to the eastern states from southern Europe failed to establish the culture of the plant there.

Types and Varieties of Alfalfa. Five general groups of alfalfa are commonly recognized. Since these groups differ materially in their climatic requirements, and especially in their abilities to survive under low temperature conditions, they will be discussed briefly. These groups are the yellow-flowered, the common, the Turkestan, the variegated, and the nonhardy. All of these alfalfas with the exception of the yellow-flowered group are classified as *Medicago sativa*, or as cultivated alfalfas. The yellow-flowered alfalfas belong to the species *Medicago falcata*. They are frequently referred to as "Siberian alfalfas," although not all yellow-flowered alfalfas come from Siberia.

The yellow-flowered alfalfas are of comparatively little agronomic importance. They are hardy and able to survive under dry conditions. Their chief value is for hybridizing with the purple-flowered types.

The common alfalfas are grown extensively over a wide range of conditions. This group includes the ordinary purple-flowered smooth alfalfa. Regional strains are designated by their place of origin such as Kansas-grown, or Idaho-grown, and differ primarily in their tolerance to low temperatures. Northern-grown common alfalfas are generally recognized to be more winter-hardy than southern-grown strains. As a matter of fact, a good many failures with alfalfa in northern areas can often be attributed to the use of southern-grown seed. The production of alfalfa seed from fields seeded with northern-grown seed in southern areas can be utilized in providing northern regions with an adapted source of seed. Such a program of seed production would not lead to immediate reductions in the winter-hardiness of the plants. Common alfalfas have a rapid rate of recovery after cutting.

The Turkestan alfalfas have been developed in Russian Turkestan. They are quite similar in appearance and climatic adaptation to the common alfalfas except that they may be somewhat shorter and more spreading in habits of growth, and slightly more hairy. Certain strains of Turkestan alfalfa are highly resistant to bacterial

wilt of alfalfa (*Aplanobacter insidiosum*) and are of special value for that reason. They are winter-hardy in northern areas. The Turkestan alfalfas are generally characterized by a slow recovery after cutting.

The variegated group includes the alfalfas that have originated from crosses between common and yellow-flowered species. These alfalfas exhibit a range of flower colors, hence the name "variegated"; most of the flowers are purple, as are the common alfalfas; others show a variety of colors from white to yellow or a combination of colors. The variegated alfalfas are known for their cold resistance. However, they differ but little in this from northern-grown common strains. The variegated varieties do not generally recover as rapidly after cutting as the common alfalfa.

The nonhardy alfalfas, as the name indicates, lack in winter-hardiness and are for that reason confined to the southern portion of the United States. In areas with mild winters redeeming features that make them of value include their long periods of growth, their ability to make a more rapid growth under short days than the hardier northern strains, and especially their very rapid recovery after cutting. For these reasons the nonhardy alfalfas are able to produce a larger number of crops per season under southern conditions than the other groups.

Climatic Relationships. Alfalfa is grown over a wide range of temperature and moisture conditions. It is an important crop from the southern valleys of Arizona and California to the prairie provinces of Canada, or from BWh to the Dfb and from the EB′d to the CC′d climates. High summer temperatures alone do not set limits to alfalfa production, nor do low winter temperatures. High summer temperatures combined with even moderate humidity, on the other hand, are very effective in excluding the crop since such conditions favor the development of stem and leaf diseases and also since a combination of high temperatures and high atmospheric humidity is favorable to the rapid development of many weedy plants which serve to smother out the alfalfa.

Alfalfa is not excluded from humid areas. The crop has become of increasing importance in the eastern portion of the United States during the past 20 years. However, the production of alfalfa in such areas is possible only under proper soil conditions, with special reference to reaction, availability of phosphates, and drainage features.

The deep and extensive root system of alfalfa gives the crop an advantage over leguminous crops with comparatively shallow root systems, such as the true clovers, in areas where surface moisture is deficient. This accounts for the great importance of alfalfa in areas too dry for the production of red clover. The area of distribution of the true clovers in the United States ends rather abruptly as the dry plains are approached, while alfalfa is a crop of great importance in the plains states. However, in dry areas yields of alfalfa decrease rapidly upon the exhaustion of the moisture supply in the subsoil.

Soil Relationships. Alfalfa is very specific in its soil requirements. It is especially sensitive to soil acidity and rarely grows to advantage at *p*H levels below 6. On the other hand, it tolerates alkali and salt concentrations better than most other crops, especially after the plants are once well established.

Alfalfa is quite adverse to phosphorus deficiencies in soils. Likewise, on extremely sandy soils potash may often constitute a limiting factor.

The crop demands a deep, well-drained soil. Deep soils capable of storing an abundance of moisture are especially desirable when the crop is grown in subhumid or semiarid areas. Poor drainage limits root development and provides conditions favoring the heaving out of plants during the winter and early spring months.

Distribution for Forage Production. Statistical data on the world distribution of alfalfa, like those on other forage crops, are scarce, and even when obtainable are subject to rather wide errors. Statistics of production by countries will not be presented, therefore.

The climatic adaptations of alfalfa make it one of the most important of all forages in areas with relatively dry climates, both in warm and in winter-cold areas. This makes the crop of special importance in the drier portions of India, in central Asia, Persia, Turkestan, and Asia Minor; throughout all of the Balkan area and in southern Russia; in the Mediterranean and adjoining areas; and in this hemisphere in Argentina, Chile, Peru, Mexico, the United States, and Canada. In some of these areas, notably in India and the Mediterranean region, the production of alfalfa is not as important as the production of cereals. This is to be attributed, not to any shortcomings of alfalfa as a crop, but to the fact that these areas do not specialize in the production of livestock.

The growing of alfalfa and the production of livestock go hand in hand. The livestock industry in the western portion of the United States and on the plains of Argentina furnishes notable examples. The importance of alfalfa in Argentine agriculture is indicated by the fact that that South American Republic, with a much smaller area adapted to the production of alfalfa than the United States, is credited by Spafford (12) with 13,353,907 acres of alfalfa for the season of 1933–34 as compared with only 11,669,000 acres in the United States in 1934.

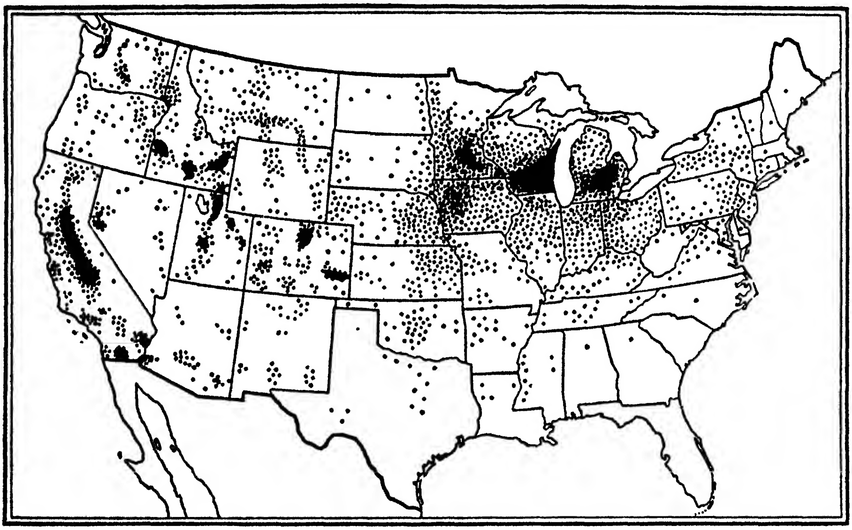


Fig. 98. Distribution of alfalfa hay production in the United States in 1938. Each dot represents 10,000 tons.

The production of alfalfa is by no means limited to relatively dry areas; owing to the special merits of the crop its production has increased rapidly in humid temperate areas both in Europe and in North America. Prior to 1920, alfalfa, with a few exceptions, was classed as a crop of the Great Plains and western states. The crop was grown at that time in but a few favored areas such as in central New York, south central Minnesota, and northern Mississippi and Alabama, but it was confined in these localities to relatively narrow limits. Since 1920, alfalfa has become, however, a crop of considerable importance in the Corn Belt and in the northeastern dairy regions. Many producers in the intense livestock producing areas of the northeastern states, after recognizing the

merits of alfalfa, have found it to their advantage to modify their soil conditions to make alfalfa production possible. This is evident from Fig. 98, giving the distribution of alfalfa production in the United States in 1938, and from Table 57, giving the statistics of alfalfa hay production by states for the ten-year period 1928–1937.

Because of prevailing droughts and prevalence of disease, particularly bacterial wilt, the production of alfalfa has decreased in the Great Plains area during the past decade. In 1938, nine states east of the Great Plains area were among the 20 highest alfalfa producing states of the country. Alfalfa production has also shown rapid increases in the eastern humid provinces of Canada during the past 20 years.

The production of alfalfa hay in the western states is concentrated in the irrigated areas of these states. In many of these areas alfalfa is not only the most important hay crop produced but is also the only hay crop. The merits of alfalfa in these areas are so outstanding as to virtually exclude all other possible hay producing crops.

TABLE 57. ALFALFA HAY: ACREAGE HARVESTED, YIELD PER ACRE, PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGE AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	*States*	*Acreage Harvested 1928–1937*	*Yield, in Tons*	*Production*		
				Average 1928–1937, in Tons	Percentage of U. S. Total	1938, in Tons
1	California	761	3.94	2,985	12.39	3,105
2	Idaho	774	2.44	1,886	7.83	1,992
3	Nebraska	1,132	1.54	1,758	7.30	1,144
4	Minnesota . . .	814	1.72	1,418	5.88	2,715
5	Iowa	656	2.09	1,338	5.55	1,934
6	Colorado	709	1.88	1,337	5.55	1,388
7	Michigan	818	1.54	1,256	5.21	1,729
8	Kansas	732	1.57	1,154	4.79	690
9	Wisconsin	583	1.95	1,114	4.62	2,758
10	Montana	686	1.57	1,083	4.49	1,083
	Other states . . .	4,777	1.84	8,768	36.39	10,341
	Total U. S. . . .	12,442	1.94	24,097	100.00	28,879

Alfalfa Seed Production. The production of alfalfa seed is a highly localized industry. According to Stewart (13) "from 80 to 90 per cent of all of the alfalfa seed produced in North America

is grown in eleven areas." Even in the specialized seed producing areas wide fluctuations in yields are experienced from season to season. In short crop years the seed supply of the United States is supplemented by imports from Argentina and occasionally from Turkestan and Italy.

Alfalfa may be designated as being extremely temperamental with regard to its seed producing habits. Though the plant demands a considerable amount of moisture for the production of several crops of hay per season, such stimulation of vegetative growth by

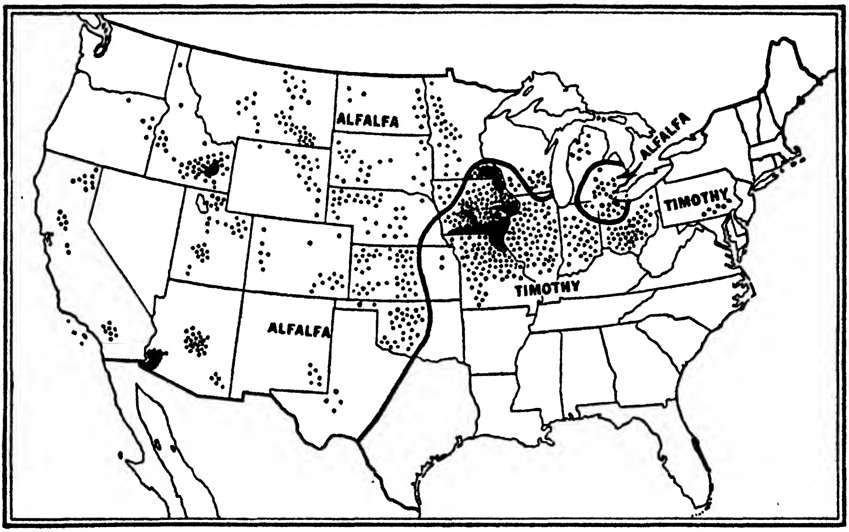


Fig. 99. Distribution of alfalfa and timothy seed production in the United States. Average for the ten-year period 1928–1937. Each dot represents 2,000 bushels.

the presence of abundant supplies of moisture is unfavorable to fruiting and seed production. As a result, the major portion of the seed crop is grown under semiarid conditions or under conditions where soil moisture supplies can be regulated by means of irrigation. Alfalfa, to produce seed, must have a constant supply of moisture to draw upon, but this moisture must not be so readily available as to induce rapid and excessive vegetative growth. The control of soil moisture alone does not ensure a seed crop. Atmospheric humidity, availability of sunlight, and the presence of insects — both helpful, facilitating pollination and cross fertilization, and harmful, causing the abortion of flowers or destruction of formed seeds — are other important factors. Rapid drying fre-

quently causes flowers to drop before fertilization can take place. Bright sunshine probably facilitates the tripping of flowers, which is necessary before pollination can be accomplished.

TABLE 58. ALFALFA SEED: ACREAGE HARVESTED, YIELD PER ACRE, PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGE AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	*State*	*Acreage Harvested*	*Yield, in Bu.*	*Production*		
				Average 1928–1937, in Bu.	Percentage of U. S. Total	1938, in Bu.
1	Idaho	37.10	2.8	104.82	11.14	64.00
2	Kansas	56.40	1.8	104.43	11.10	118.00
3	Arizona	19.86	4.9	96.70	10.28	107.00
4	Montana	39.80	2.0	81.22	8.63	42.00
5	Nebraska	47.00	1.4	64.59	6.87	92.00
6	Utah	33.03	1.9	63.87	6.79	105.00
7	Oklahoma	25.20	2.5	62.97	6.69	138.00
8	Minnesota	40.38	1.4	57.82	6.15	57.00
9	California	15.19	3.4	51.54	5.48	60.00
10	South Dakota	41.17	1.0	46.68	4.96	4.00
	Other states	130.77	1.6	206.10	21.91	247.00
	Total U. S.	485.90	1.96	940.74	100.00	1,034.00

Table 58 gives the United States statistics of alfalfa seed production by states. Figure 99 shows the seed producing areas cartographically. With few exceptions the alfalfa seed crop of the United States is produced in the western half of the country. Limited amounts of seed are produced in northern Michigan, southern Michigan, and northern Ohio, in Wisconsin, and in occasional years, in Indiana and Illinois. It is evident from Table 58 that the relative importance of seed production in the southern Great Plains area has been increasing in recent years. Compare the 1928–1937 production with the production in 1938. Idaho dropped from first place to sixth place in volume of production, while Oklahoma rose from seventh to first place. Kansas and Arizona maintained their places. In this connection it must, however, be recognized that the volume of production of alfalfa seed for any given state is subject to considerable variation from one season to another.

THE CLOVERS

The true clovers belong to the genus *Trifolium*. This genus contains a large number of species. Hunt (4) estimates around 250 such species. Only a limited number of them are, however, of great economic importance. The ones to be considered in this chapter are: red clover, alsike clover, white clover, ladino clover, and strawberry clover.

RED CLOVER

(*Trifolium pratense*)

Economic Importance. Red clover is the most widely grown biennial leguminous forage crop in American agriculture. Prior to the recent increases in alfalfa production in the northeastern quarter of the United States, red clover was the leading producer of leguminous hay. It is now surpassed by alfalfa in total tonnage produced; however, red clover, grown either in pure stands or in combination with grasses, is still being grown on a larger number of American farms than any other leguminous hay crop. The census reports of the United States do not differentiate between red, alsike, or crimson clovers. Likewise, no differentiation has been made between timothy and clover hay, grown alone or in mixtures. It is therefore impossible to designate the exact acreage of red clover grown alone. A common practice is to seed red clover with timothy or other grasses. The first year's crop from such mixtures consists largely of clover, the second year's crop of a clover-grass mixture, and if the field is left for more than two years the hay crop in the third and subsequent years consists mostly of grasses.

Red clover produces a hay of excellent quality which is valued especially on account of its high protein and mineral content. The crop is used to but a limited extent for strictly pasture purposes. Red clover is extensively employed in crop rotation systems in humid areas.

Historical. Red clover was apparently first cultivated in Media and south of the Caspian Sea, in the same general region where alfalfa was first utilized. But, unlike alfalfa, it was not known as a crop to the early Greeks and Romans. Its employment in European agriculture is also comparatively recent, the first mention of its use being made by Albertus Magnus in the thirteenth century.

According to Piper, there are definite records of its cultivation in Italy in 1550, in Flanders in 1566, and in France in 1583. It was not introduced into England until 1645. Red clover was probably introduced into the United States by the early English colonists. Jared Elliot wrote of its culture in Massachusetts in 1747.

The importance of the introduction of red clover into European agriculture is stated by Piper (11) in the following paragraph.

> "Its introduction into European agriculture had a profound effect in that clover soon came to be used in rotations in place of bare fallow. Its influence there on agriculture and civilization is stated by high authority to be greater than that of the potato, and much greater than that of any other forage plant. Clover not only increased the abundance of animal feed and therefore of manure, but also helped greatly by adding nitrogen to the soil directly."

Merkenschlager (7), however, points out that even red clover with its outstanding merits as a feed and soil-improvement crop had a considerable grower resistance to overcome before its culture was generally adopted in central Europe.

Climatic Relationships. Red clover, like all the true clovers, is a moisture-loving crop. Its production is strictly limited to humid areas or to locations where irrigation is practiced. In irrigated areas it takes a secondary place to alfalfa as a producer of hay, being grown there mostly for seed production, and in places where drainage features eliminate alfalfa as a hay crop. Red clover has been designated as a crop of marine climates; however, Merkenschlager points out that it does not do well in Europe in the close proximity of coastal areas where fogs are common. According to Merkenschlager, serradella is better adapted to such areas, while red clover occupies the humid areas favored with a greater abundance of sunlight, located between cloudy and foggy coastal regions and the drier areas in which alfalfa becomes the more important crop. Lack of sunshine has not been regarded as a limiting factor to red clover production in any American producing area.

Red clover demands moderate summer temperatures. In the southern portions of the United States red clover seeded in the fall behaves as a winter annual. The plants usually die by the middle of the summer following seeding. Winter temperatures encountered in the northern portion of the United States are generally not detrimental to red clover, although winterkilling is

experienced where the crop is grown on poorly drained soils and in cases where plants enter the winter in a weakened condition.

Soil Relationships. Red clover is quite specific in its soil requirements, though less so than alfalfa. The crop demands fairly good drainage. Since it requires an abundance of moisture during the growing season, soils must have good moisture-holding capacities to produce maximum crops. The crop is not adapted to extremely light sandy and gravelly soils or to very heavy, impermeable clay soils. The former are too droughty, while the latter are too poorly drained.

Red clover is a lime-loving crop. It does well on heavy soils, provided such soils contain an abundance of lime and are well drained. According to Morgan *et al.* (8), soils more acid than *p*H 5.6 rarely produce good clover crops. The chief soil factors that have restricted success with red clover, state these authors, are heavy, intractable subsoils, excessive soil acidity, and depleted mineral fertility. As in the case of alfalfa, the mineral most frequently lacking is phosphorus.

Distribution. The world distribution of red clover production is not so extensive as that of alfalfa. Red clover is a crop of humid regions with moderate temperatures. Alfalfa also does well in these

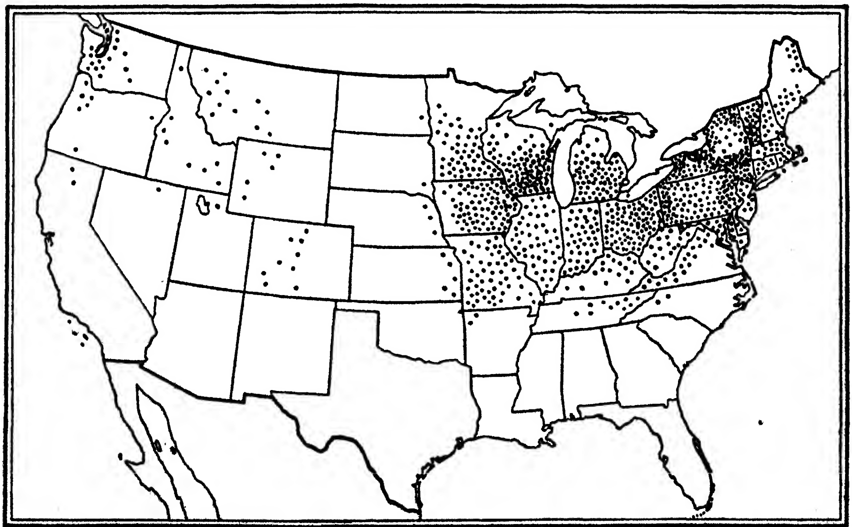


Fig. 100. Clover and timothy hay distribution in the United States. Average annual production for the ten-year period 1928–1937. Each dot represents 25,000 tons of hay.

regions when proper attention is given to its very specific soil requirements and in addition is used in areas too dry and with summer temperatures too high for the production of red clover. Its specific climatic limitations confined red clover production largely to northwestern Europe, the northeastern portion of the United States, southeastern Canada, the humid portions of the Pacific Northwest, and New Zealand.

A glance at Fig. 100 shows that the major production of clover in the United States, including red, alsike, and mammoth clovers, and timothy and timothy and clover mixed is practically confined to the area east of the Great Plains states and north of the Ohio and Potomac Rivers. Some clover is grown in the very northern portions of the Cotton Belt. Red clover is also of importance as a hay crop in the Willamette Valley of Oregon and in western Washington. Production in Idaho is primarily for seed. Some clover, and especially timothy and clover mixed hay, is produced in the intermountain states. Most of the production of these hays in this region are found in the irrigated valleys and on mountain meadows, in locations where drainage features are unfavorable to the growing of alfalfa. The leading clover and timothy hay producing states are given in Table 59.

TABLE 59. CLOVER AND TIMOTHY HAY: ACREAGE HARVESTED, YIELD PER ACRE, PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGE AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	States	Acreage Harvested	Yield, in Tons	Production		
				Average 1928–1937, in Tons	Percentage of U. S. Total	1938, in Tons
1	New York	3,282	1.20	3,940	14.82	4,266
2	Wisconsin	2,195	1.25	2,816	10.60	3,010
3	Pennsylvania	2,220	1.16	2,583	9.72	2,686
4	Iowa	1,910	1.09	2,126	8.00	1,844
5	Ohio	2,056	0.98	2,014	7.58	2,411
6	Michigan	1,548	1.02	1,587	5.97	1,735
7	Missouri	1,870	0.78	1,469	5.53	1,071
8	Illinois	1,286	1.08	1,401	5.27	1,688
9	Minnesota	1,013	1.20	1,220	4.59	1,098
10	Indiana	1,102	0.95	1,050	3.95	1,401
	Other states	5,499	1.15	6,371	23.97	6,575
	Total U. S.	23,981	1.10	26,577	100.00	27,785

Seed Production. Table 60 gives the statistics on red and alsike clover seed production in the United States for the ten-year period 1928–1937. About three times as much seed of red clover as of alsike is produced. Both of these clovers are grown in the same general sections, the red being produced on lands with good and the alsike clover on soils with poorer drainage. Of the leading seed producing states listed in Table 60, Minnesota alone produces more alsike than red clover. Alsike clover seed production approaches

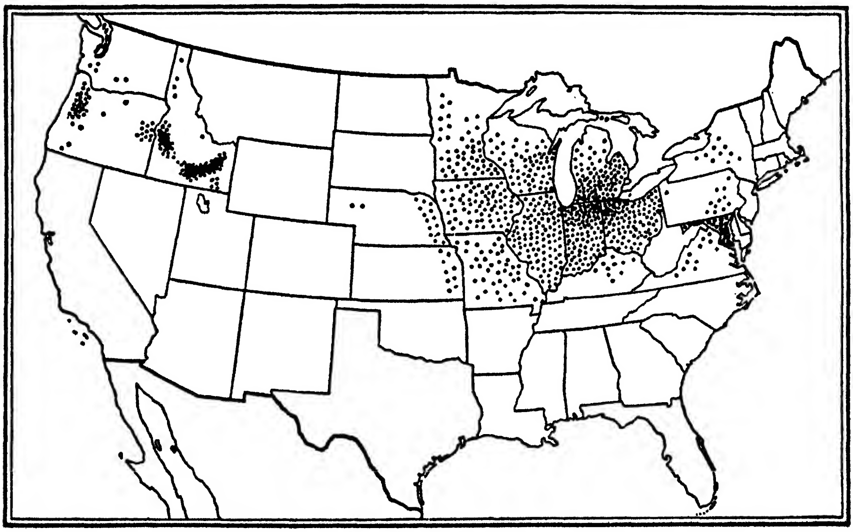


FIG. 101. Distribution of red clover seed production in the United States. Average for the ten-year period of 1928–1937. Each dot represents 1,000 bushels.

the amounts of red clover produced in Ohio and in Oregon. However, in all of the leading seed producing states the acreage devoted to red clover seed exceeds that devoted to alsike. Figure 101 gives the red clover seed producing areas of the United States.

Seed production of red and alsike clovers is concentrated in the eastern and central portions of the Corn Belt. Only two states not located in the northeastern quarter of the country are important producers of clover seed, namely, Idaho and Oregon. The crop is grown under irrigation in the Snake River Valley of Idaho and in eastern and central Oregon. It is grown under natural rainfall conditions in the Willamette Valley of western Oregon and in the northern portion of Idaho. In the Corn Belt an early crop of hay is generally harvested and the second crop is used for seed produc-

tion. In the irrigated sections of Idaho and Oregon the red clover fields designed for seed production are commonly pastured until the end of May or into early June and then allowed to make seed.

TABLE 60. RED AND ALSIKE CLOVER SEED: ACREAGE HARVESTED AND PRODUCTION EXPRESSED IN THOUSANDS — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937

Rank	States	*Red Clover*			*Alsike Clover*		
		Acreage Harvested	Production, in Bu.	Percentage of U. S. Total	Acreage Harvested	Production, in Bu.	Percentage of U. S. Total
1	Indiana	157.00	149.00	14.91	9.10	11.30	3.37
2	Illinois	125.00	113.00	11.31	14.00	19.00	5.67
3	Ohio	112.00	111.00	11.11	59.00	91.00	27.14
4	Michigan	103.00	111.00	11.11	22.00	36.00	10.74
5	Idaho	25.00	111.00	11.11	1.90	10.70	3.19
6	Iowa	103.00	85.00	8.51	4.60	7.50	2.24
7	Wisconsin	57.00	68.00	6.81	21.00	39.00	11.63
8	Minnesota	35.00	50.00	5.01	29.00	80.00	23.86
9	Oregon	19.60	44.00	4.40	9.40	35.00	10.44
10	Missouri	44.00	42.00	4.21	2.10	3.00	0.89
	Other states	93.40	115.00	11.51	1.40	2.80	0.83
	Total U. S.	874.00	999.00	100.00	173.00	335.00	100.00

Red clover seed is also produced in western Europe. The most important producing countries are France, Germany, Poland, and Italy. European clover seed is from time to time imported into the United States. These European red clovers are, under most conditions, inferior in their performance to domestic strains. Those originating from southern France and from Italy especially lack in winter-hardiness when grown in the northeastern portion of the United States. Aamodt *et al.* (1) point out that the European red clovers are decidedly inferior to domestic strains in their ability to produce good stands during years of seeding when droughts and high temperatures prevail.

ALSIKE CLOVER
(*Trifolium hybridum*)

Historical. Alsike clover is a native of northern Europe. It has long been cultivated in Sweden; its spread into other agricultural areas has, however, been relatively recent. The production of

alsike clover was not recorded in England and Scotland until in 1832. Emigrants from northern Europe no doubt brought seed with them to the United States. Seed was distributed in the United States by the Patent Office in 1854.

Utilization. Alsike clover is used for the same purposes as red clover. Since, however, it is longer lived and more persistent, alsike clover is used more extensively than red clover in pasture mixtures.

Adaptation and Distribution. Piper ascribes a wider range of adaptation with regard to temperature and moisture relationships to alsike than to red clover. This holds true insofar as alsike clover is able to survive under somewhat lower winter temperatures than red clover. Alsike will also grow on wet, and even poorly drained, soils not suited to the growth or survival of red clover. However, there is little, if any, difference in the drought resistance of these two crops and in their unfavorable reaction to high summer temperatures. Both red and alsike clovers prefer cool climates and an abundance of moisture during the growing season.

While alsike clover responds to applications of lime, it is not as sensitive to soil acidity as red clover. This characteristic, together with the fact that the crop can be grown in areas with relatively poor drainage features, gives alsike clover a wider range of adaptation to soil conditions than red clover. This enables the growing of alsike in areas not adapted to red clover and in places where red clover culture has dwindled on account of "clover failure," or on soils commonly designated as being "clover sick."

Alsike clover is a crop of considerable importance in the cool and relatively moist regions of northwestern Europe. In the United States and Canada it is grown in the same general areas as red clover. Table 60 gives the production of alsike clover seed by states.

WHITE CLOVER

(*Trifolium repens*)

White clover is another leguminous plant native to northwestern Europe that has been introduced to all moist temperate areas of the world where it is being made use of extensively in pastures and lawns. It is a long-lived perennial, a prolific seed producer, and is normally found growing in association with grasses. On account of its abundant seed production it occurs naturally in many pastures

without having been included in the pasture mixture sown. In other words, it is designated as occurring "spontaneously."

White clover has the same general climatic and soil adaptations and is found in the same general regions as red clover. Where moisture is abundant it does well, even in sections with relatively high summer temperatures as in Louisiana and Florida where it is used for winter pasturage.

According to Hollowell (2) the United States uses between 2 and 3 million pounds of white clover seed annually. Around 95 per cent of it is used in lawn-seed mixtures. About half of the seed used in this country is of foreign origin, most of it coming from Poland and from other north European countries and from the British Isles. Hollowell enumerates three principal seed producing regions of the United States in order of their relative importance: (1) Louisiana; (2) Idaho, Oregon, and Washington; and (3) the northern Corn Belt states, principally Wisconsin.

LADINO CLOVER

(*Trifolium repens var. latum*)

Ladino clover is a large form of white clover used primarily for pasture and to a limited extent for hay. The crop is adapted to the same general area as white clover, except that, since it is not so winter-hardy, its region of production does not extend as far to the north. However, ladino clover is more winter-hardy than formerly supposed. It is being successfully used in pasture mixtures in southeastern Idaho at elevations of above 4,000 feet where winter temperatures occasionally drop down to − 30°F. It is also grown with success in the central portion of the Corn Belt and to the east.

Ladino clover is adapted to a great variety of soils. It makes a very rapid recovery after being grazed off. Like white clover the crop is shallow-rooted and demands an abundance of moisture. It is ideally adapted to irrigated pastures.

According to Madson and Coke (6), the origin of ladino clover is not definitely known. It has been grown in the upper valley of the Po of northern Italy for more than 50 years. It probably developed there by a process of natural selection from White Dutch clover. Seed for trial in this country was first secured by the United States Department of Agriculture in 1903. The crop,

however, attracted no great attention until after 1920. In the past ten years the interest in ladino clover as a pasture plant for naturally well-watered and irrigated soils has been increasing rapidly. Most of the seed crop of ladino clover in this country is produced in southwestern Oregon and in the Snake River Valley of Idaho.

STRAWBERRY CLOVER

(*Trifolium fragiferum*)

Strawberry clover, a native of the eastern Mediterranean area and of Asia Minor, is another recent introduction to the United States. It is adapted to the same general region as white clover and is used for the same agronomic purposes. The special feature of strawberry clover, as pointed out by Hollowell (3), is its tolerance to seeped, saline, and alkaline soils containing concentrations of salts that inhibit the growth of most other crop plants. This characteristic makes strawberry clover of special importance in the irrigated sections of the western states. The crop thrives, however, only in places where moisture is abundant.

OTHER BIENNIAL AND PERENNIAL LEGUMINOUS CROPS

Sweet Clover (*Melilotus spp.*). The two species of biennial sweet clover of special agronomic importance are the white (*M. alba*) and yellow (*M. officinalis*). Both are used extensively for pasture and soil improvement purposes and to a limited extent for hay production.

Sweet clover offers an interesting example of a plant that has been elevated from the position of a weed, of common occurrence along roads, fences, and irrigation ditches, to a field and pasture crop of considerable importance. Sweet clover, or Bokhara melilot as it is also called, originated in western Asia, in the same general territory where alfalfa was first cultivated. Piper indicates that it was introduced into North America as early as 1739, when it was reported in Virginia. The extensive utilization of the plant as a field crop, however, dates back only about 30 years.

Sweet clover has a wide range of climatic adaptation and is also found on a great variety of soils. It does best, however, on soils of neutral or slightly alkaline reaction. It thrives well and is made

use of to advantage in both humid and semiarid regions. It withstands high summer temperatures and is also winter-hardy. As a result it is used more or less over the entire area of the United States. It assumes a place of special importance in the Great Plains area where it is considered one of the valuable legumes for increasing the nitrogen and organic matter contents of cultivated land. The true clovers are excluded from this area by the lack of a sufficient amount of moisture for their growth requirements; their places are taken to a large degree by the deep-rooted sweet clover. Sweet clover is also of considerable importance in the Corn Belt where it is used to advantage for the production of summer pasturage and for soil-improvement purposes. The Great Plains states are also of prime importance from the standpoint of seed production of the crop, though some seed is produced in the Corn Belt. The leading seed producing states of the country together with their production of seed in thousands of bushels for the ten-year period of 1928–1937 are: Minnesota, 289.3; North Dakota, 139.4; South Dakota, 109.8; Nebraska, 55.1; Kansas, 47.7; and Illinois, 40.7.

Sericea (*Lespedeza sericea*). This perennial lespedeza was introduced into the United States from Japan in 1896 and in 1899. Sericea produces a fairly woody type of growth, somewhat lacking in palatability, which may be utilized for pasture and, when cut early, for the production of hay. The main use of the crop is to control erosion and provide feed and cover for wild life. According to Pieters (10), sericea thrives best on clay loams and silt loams but has made good growth on sands and sandy loams and has done well on some acid muck soils. It demands good soil drainage. Since it is not winter-hardy and not particularly drought-resistant, its culture is confined to the southeastern quarter of the United States.

Kudzu (*Pueraria thunbergiana*). Kudzu is a perennial, hot-weather, leguminous vine native to Japan. Like sericea, it was introduced into the United States during the latter part of the last century. It has found a place in the southeastern states as a pasture and soil-improvement crop and also to some extent as a hay crop. Its place of usefulness is confined to the humid portions of the Cotton Belt. While kudzu can be grown in the central portion of the Corn Belt, it cannot be expected to compete successfully

there with either alfalfa or the clovers. Kudzu, according to Pieters (9), thrives on many types of soil and has the special merit of being able to make good growths on soils too acid for alfalfa and the clovers. Seed production in the United States is rare; for that reason the crop is generally established vegetatively from rooted plants.

Sanfoin (*Onobrychus viciaefolia*). Sanfoin, also known as esparcet or esparsette, is native to the southern half of Europe and eastward to Lake Baikal. While sanfoin has been grown experimentally in numerous tests in this country, it has not become commercially established. According to Kutscher (5), it is grown quite extensively in southern and central Europe where it is considered of special value on dry, porous, calcareous soils. The crop is slower to establish itself than alfalfa; full yields are generally not obtained until the third or even fourth year after seeding.

Lotus. Several species of lotus are of economic importance as pasture plants. Strecker (14) speaks highly of two species with regard to utilization under European conditions. *Lotus corniculatus*, or birds'-foot trefoil, is designated as being adapted to areas with severe climatic conditions, both with reference to the moisture and temperature factors. It also has a wide range of soil adaptation — from fertile, moist to dry sandy and even stony soils. Birds'-foot trefoil is being grown to a limited extent in western Oregon and Washington. *Lotus uliginosus* is especially adapted to moist and even to swampy soils.

REFERENCES

1. Aamodt, O. S., J. H. Torrie, and O. F. Smith, "Strains of red and white clovers," *Jour. Amer. Soc. of Agron.*, 31:1029–1037 (1939).
2. Hollowell, E. A., "White clover," *U. S. Dept. Agr. Leaflet* 119, 1936.
3. ———, "Strawberry clover," *U. S. Dept. Agr. Leaflet* 176, 1939.
4. Hunt, T. H., *The Forage and Fiber Crops in America.* Orange Judd Co., New York, 1908.
5. Kutscher, H., *Wiesenbau.* Paul Parey, Berlin, 1909.
6. Madson, B. A., and J. E. Coke, "Ladino clover," *Calif. Agr. Ext. Circ.* 81, 1937.
7. Merkenschlager, F., "Die Konstitution des Rotklees," *Die Ernährung der Pflanze*, 30:81–89. 1934.
8. Morgan, M. F., J. H. Gourley, and J. K. Ableiter, "The soil requirements of economic plants," *U. S. Dept. Agr. Yearbook* 1938:753–776.

9. Pieters, A. J., "Kudzu, a forage crop for the southeast," *U. S. Dept. Agr. Leaflet* 91, 1932.
10. ———, "Lespedeza sericea and other perennial lespedezas for forage and soil conservation, *U. S. Dept. Agr. Circ.* 534, 1939.
11. Piper, C. V., *Forage Plants and Their Culture.* Macmillan, New York, 1937.
12. Spafford, W. J., "Agriculture in the temperate and sub-tropical climates of the South," *Dept. Agr. So. Australia Bull.* 310, Adelaide, 1936.
13. Stewart, G., *Alfalfa-growing in the United States and Canada.* Macmillan, New York, 1926.
14. Strecker, W., *Die Kultur der Wiesen, ihr Wert, ihre Verbesserung, Düngung und Pflege.* Paul Parey, Berlin, 1923.
15. Throckmorton, R. K., and S. C. Salmon, "Alfalfa production in Kansas," *Kans. Agr. Exp. Sta. Bull.* 242, 1927.
16. Westover, H. L., "The uses of alfalfa," *U. S. Dept. Agr. Farmers' Bull.* 1839, 1940.

Chapter XXXI

PERENNIAL FORAGE GRASSES

INTRODUCTION

Appreciation of Grasses and Grassland Agriculture. The term "forage grasses" is used to designate those grasses primarily grown and utilized for hay or pasturage. Such grasses are either native to this continent or of foreign origin. With but minor exceptions the grasses now extensively cultivated on farms in American agriculture are of foreign extraction, coming mostly from Europe and Asia. They are frequently referred to as tame or cultivated grasses. Species indigenous to North America have long been utilized in their native habitats, that is, on undisturbed grasslands and on ranges in the Great Plains and western states. It is, however, only within recent years that the forage possibilities of these native grasses have been definitely investigated. While their values have been appreciated, and while they have provided the basis for the development of a thriving livestock industry in our western states, but little concerted effort has in the past been put forth toward the improvement of native species of grasses, and toward their extensive employment in the revegetation of denuded areas and abandoned crop lands.

Many of our native grasses are better adapted to our environmental conditions than imported or exotic species. Their apparent neglect is traceable to the regrettable fact that this great native resource of the grassland areas was definitely exploited rather than utilized in line with the physiological growth requirements of the grass crop. The conservation aspects of grassland management are of recent origin. Since many native species have rather poor seed habits, seed for reseeding purposes both on the range and on abandoned crop lands has been hard to obtain. More recent investigations regarding the seed producing habits of native grasses have shown that at least some of them have better seed habits than earlier

work indicated. Furthermore, the seed habits of many of them can be and have been improved upon by the selection and isolation of strains capable of producing fair to good seed yields. The forage characteristics of many native grasses have also been definitely improved upon by selection. The recent interest in the growing of grasses for soil and water conservation has given a great impetus to this line of research. Plant breeders up until the present decade have confined their interests largely to the improvements of food and fiber crops. The forage grasses, while offering opportunities for improvement as great as other crop plants, have been more or less neglected. This situation can be attributed to the great need for increased production of food and fiber crops in the past. The change in attitude, or more correctly the present interest in the possibilities of grass improvement by the application of those principles of plant genetics which have brought about such great improvements in our general field crops, is traceable to the growing realization of the value of grasses. Agricultural production in many areas is being adjusted to a grassland base. Not only is there current interest in the search for grasses capable of being established and maintained in dry areas with trying environmental conditions, but also a real effort is being made toward the improvement of grasses and their greater utilization in humid areas where their establishment generally does not offer as serious problems as in dry regions.

Grass is the climax vegetation of great expanses of land with the grassland climate often referred to. In the past, great and at times unwise expansion of crop production into these important grassland areas led to the exploitation of these valuable areas. Crop producers, and especially the producers of cereal crops, have generally been regarded as the main exploiters. This is not entirely the case; producers of livestock have also had a very definite part in this exploitation as is evident from the present depreciated condition of many range lands. There is, of course, every justification for the use of native grassland for crop production purposes in many areas; as a matter of fact some of our best agricultural lands were formerly clothed with a protective cover of grass, and such grass covers have, through the ages, contributed to the development of the very characteristics which make them usable and desirable for crop production. The place where the utilization of such grasslands for crop production cannot be justified is where the plow advanced into

grassland areas with highly hazardous climates. This aspect of land utilization has been referred to in former chapters. It is again mentioned here to bring out the fact that the necessary and often painful retrenchment of crop production from such areas not only has brought material changes in the concepts of proper land use, but also has resulted in a greater appreciation of the value of grass on such lands. To the optimist willing to gamble with the hazardous climatic conditions encountered in the dry grassland areas, it has brought a lesson in plant adaptation, in that it has convinced many would-be crop producers in these regions that grass is better adapted to the great extremes in the moisture and temperature factors than any crop plant that man may substitute. Likewise, livestock men who have allowed their ranges to be depreciated by overgrazing are realizing that it is necessary to manage their grasslands in a manner compatible with the physiological growth requirements of the plants valued on those ranges in order to prevent still greater depreciation in the future.

Improvement of these ranges is one of the real needs of western agriculture. These improvements of the native grasslands must be based on the physiological growth requirements of the grasses. While adapted species of grasses are generally tenacious and even aggressive under favorable conditions, they are unable to withstand prolonged abuse. The reseeding of such grasslands must be resorted to in extreme cases, that is, where the desired species have disappeared entirely. Usually, however, where some of the desired species still remain, the most rapid and certain improvement can be accomplished by alterations in management. Grasses in order to become established and to be able to maintain themselves must be given opportunities to produce seed periodically. The seedlings resulting from periodic seed production must also be given a chance to establish themselves. Furthermore, if a vigorous growth of grasses is to be expected, the established plants must be allowed opportunities to build up their organic reserves. In addition, the feed to be expected from range areas should be supplemented in many areas by supplies of feeds produced on nearby crop lands. Such supplementary feeds may consist of hay, pasturage, or even of concentrates.

The above offers a few examples of the growing appreciation of the value of grasses in dry regions. Grassland agriculture also has

its ramifications in humid areas not only from the standpoint of providing feed for livestock, but also for erosion control and for providing a crop of value in rotation systems. The fibrous roots of grasses have a very favorable effect on the structure of the soil. While leguminous plants have a higher value as producers of hay on account of their greater protein and mineral contents than strictly grass hays, the two are often grown to advantage in mixtures. This brings out the good features of both of these important forage crops. Likewise, grasses form a valuable constituent of nearly all pasture mixtures. The term "grassland agriculture," or the adjustment of crop and livestock production to a grassland base, is now used frequently in relation to the establishment of permanent systems of agricultural production. It is a good term, and agriculture has much to gain by making use of the concepts inferred by it. The adjustments called for in the establishment of a grassland agriculture have already been made in many of the older agricultural areas of the United States interested in the production of both cash crops and livestock products. It is the system that has long been utilized in most of the agricultural sections of northwestern Europe, and it accounts to no small degree for their agricultural stability. The term "grassland" in this connection applies to the production of both grasses and legumes either in pure stands or in mixtures.

Many Species of Grasses Available. The members of the grass family show a great diversity in form, desirable characteristics, growth requirements, and the manner in which they may be utilized. Some indication of the diversity and numbers of the members of the grass family is given by the fact that Hitchcock (4) lists 159 genera and 1,100 species known to be growing in the continental United States, excluding Alaska. The range of usefulness of grasses is given by a classification of their uses. Thus, Hitchcock enumerates the various uses to which grasses are put, as food grasses, hay grasses, pasture grasses, soiling grasses, silage grasses, range grasses, grasses used in industrial arts, soil-holding grasses, grasses for lawns and golf courses, and ornamental grasses.

Because of the great number of grasses occurring in native environments and propagated by man, the distribution of only a limited number can be discussed in this chapter.

GRASSES OF COOL, HUMID REGIONS

Timothy (*Phleum pratense*). Timothy is the most widely cultivated hay grass in American agriculture. Since it will not stand close grazing and the trampling by animals incident to grazing, it is not used to any great extent in pasture mixtures. Timothy is indigenous to most of Europe, temperate Asia, and parts of northern Africa. Even though timothy is not native to North America, its value as a cultivated plant was first recognized in the United States. The name "timothy" was given to the plant during colonial times, apparently after one Timothy Hanson, who is reported to have brought the grass from New England into Maryland. It is now grown in meadows over wide areas in Europe, but especially in northern areas and at high elevations. Timothy is regarded as a valuable grass in the British Isles, in Germany, and particularly in the Scandinavian countries. Armstrong (1) reports that it has been found very suitable on good lands in the mountain valleys of Norway, and that it is being grown with success in Sweden, even in the latitude of the Polar Circle. Timothy is more cold-resistant than most cultivated grasses. While timothy is considered of value in Europe on moist, fertile soils, it is not grown as extensively there as in the United States.

Since timothy has the same general soil and climatic adaptation as red clover, it is commonly grown in combination with that crop. The distribution of timothy and timothy-clover mixed hay is shown in Fig. 100, while the distribution of timothy seed production is shown in Fig. 99, Chapter XXX. The leading seed producing states are Iowa, Missouri, Illinois, Minnesota, and Ohio.

The southern limits of timothy production are determined by its inability to tolerate high summer temperatures. It is very effectively eliminated by a combination of high summer temperatures and high atmospheric humidity. This accounts for the fact that the bulk of the timothy crop of the United States is produced north of the Ohio and Potomac Rivers.

Timothy is a moisture-loving plant. Like red clover, it demands fair to good soil drainage. The western limits of production in the United States are definitely determined by the availability of moisture during the growing season; its region of distribution ends rather sharply in the very eastern portions of the states of the Great

Plains area. The crop is grown to some extent in well-watered localities in the northern Mountain states and also in the humid Pacific Northwest. In western Oregon and Washington, however, it is of less importance than in the northeastern quarter of the United States.

The Bent Grasses (*Agrostis spp.*). Several species of *Agrostis* are utilized for hay, pasture, and lawn purposes. Redtop (*A. alba*) is by far the most extensively used species in this country. However, creeping bent, designated by Hitchcock as *A. palustris* and by Armstrong as *A. alba*, var. *stolonifera*, is the most important species used in the cool, humid portions of Europe.

Redtop is grown in the same general territory as timothy and is subject to the same climatic limitations in its distribution. Since it does well on wet and acid soils, it is frequently grown in combination with alsike clover. Redtop is of special importance in the New England states and in southern Illinois. Most of the seed of the United States is produced in the latter area.

Redtop is used for the production of hay and pasturage. It withstands close grazing and trampling better than timothy. Redtop, according to Piper (8), is second only to bluegrass as a pasture plant in the northeastern part of the United States. It is a vigorous grower and forms a good turf in a short time.

Piper (8) ascribes a wide range of adaptation to redtop with respect to the soil and moisture factor, indicating that it is one of the best of wet-land grasses and also "strongly drought resistant." That the grass has a wide range of soil adaptation cannot be denied. As a matter of fact, its ability to grow on a great variety of soils and especially in wet places constitutes one of its chief points of merit. On the other hand, it is evident from the distribution of the grass that the western limits of redtop production are nearly as effectively determined by low rainfall in the eastern Great Plains area as are those of timothy. Redtop, like timothy, is a moisture-loving plant. It is difficult to establish stands of the grass under low rainfall conditions.

Creeping bent, while regarded of great value as a pasture and hay grass in northern Europe, is used for that purpose to but a limited extent in the United States. The grass demands an abundance of moisture and moderate temperatures; its agricultural use is for that reason largely confined to seaside meadows on the

northern Atlantic and Pacific coasts. Creeping bent is highly valued as a lawn grass in all of the northern portions of the United States and is extensively used for that purpose in places where an abundance of moisture is available. In its ability to produce a fine-textured lawn, it is surpassed only by the still finer leaved velvet bent (*A. canina*). While these two bent grasses produce beautifully textured lawns under favorable conditions and with proper care, they are more exacting in their environmental requirements than Kentucky bluegrass. Furthermore, the bent grasses do not start growth as early in spring or remain green as long in the fall as Kentucky bluegrass.

Colonial, also designated as Rhode Island bent (*A. tenuis*), is extensively employed as a pasture grass in the New England states and in New York. Unlike redtop, the colonial bent demands well-drained soils; it is similar to redtop in that it thrives on acid soils. Colonial bent is less tolerant than redtop of high summer temperatures and is for that reason confined in its distribution to northern areas.

The Bluegrasses (*Poa spp.*). Kentucky bluegrass (*P. pratensis*) is the most widespread pasture and lawn grass of the northern humid portions of the United States and also occurs in all irrigated areas in the northern portion of the country. It has been so widely distributed that it has become a natural component of most humid and irrigated pastures, so much so that it appears "spontaneously" in pastures and meadows and often in places where it is not wanted. Kentucky bluegrass is very aggressive; while this is a desirable characteristic in pasture grasses, Kentucky bluegrass frequently crowds out more desirable species in both pastures and meadows. The greatest point of weakness of the grass is that it languishes during periods of summer heat. Where species capable of enduring relatively high summer temperatures, such as orchard grass, brome grass, and meadow fescue, are replaced by the aggressiveness of Kentucky bluegrass, the carrying capacities of such pastures are reduced. Likewise, hay yields of meadows are frequently reduced by Kentucky bluegrass invasions.

Kentucky bluegrass is markedly resistant to cold. Consequently its distribution to the north is not limited by severe winter conditions. On the other hand, high summer temperatures determine its southern range of usefulness. Consequently, it is not utilized to

any great extent farther to the south than timothy. Likewise it is definitely a grass of humid regions; dry conditions in the eastern Great Plains area set a rather clear-cut limit to its western range of distribution. In Europe the grass is valued for its drought resistance. This is a comparative concept in that many of the moisture-loving grasses extensively employed in European agriculture are effectively eliminated in our agricultural regions by the significantly higher summer temperatures prevailing even in the humid portions of the northeastern quarter of the United States. Piper (10), in speaking of the prominent places occupied by Kentucky bluegrass, our most important pasture and lawn grass, and timothy, our most important hay grass, makes the following worthwhile observation: "It is difficult to find a satisfactory explanation for the great importance of this grass and of timothy in America. About all that can be said is that these two grasses are much better adapted to the climatic conditions of cold winters and hot summers than are any other European grasses used for the same purposes." In comparing the relative distribution of grasses used in European and American agriculture it is well to keep in mind that northwestern Europe has marine and littoral climates while the climates of the northeastern quarter of the United States have distinct continental aspects. In Europe the rough-stalked meadow grass (*P. trivialis*), a species of little importance in the United States, is more widely used than Kentucky bluegrass.

Canada bluegrass (*P. compressa*) is adapted to the same range of climatic conditions as Kentucky bluegrass. It is, however, somewhat more resistant to summer heat and drought than Kentucky bluegrass and will also grow on poorer soils. Kentucky bluegrass prefers well-drained soils and soils rich in humus. In places Canada bluegrass may be regarded more as a weedy grass than as a grass of agricultural importance.

In addition to the three species of *Poa* indicated above, two native drought-resistant species of this genus, big bluegrass (*P. ampla*) and Sandberg bluegrass (*P. secúnda*), are beginning to be utilized on the dry lands of the Pacific Northwest. Texas bluegrass (*P. arachnifera*) is used to some extent in the southern Great Plains area where it is valued for its ability to endure high summer temperatures. Fowl meadow grass (*P. palustris*), a native of both Eurasia and North America, is of value only in moist localities of northern areas.

Orchard Grass (*Dactylis glomerata*). Orchard grass is not as winter-hardy as either timothy or Kentucky bluegrass. Its northern limit of usefulness coincides quite well with the northern portion of the Corn Belt. Since, however, the grass is fairly tolerant of high summer temperatures, it can be grown to advantage to the south, even in the northern Cotton Belt. Orchard grass is also more drought-resistant than timothy; however, this difference is not great enough to affect a significantly greater westward distribution

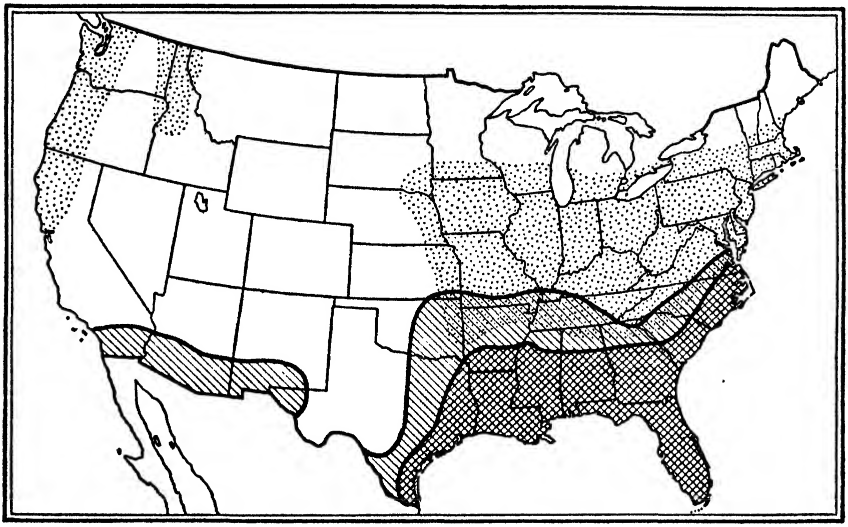


FIG. 102. Region of distribution of orchard and tall oat grasses, dotted; bermuda, single lined; and carpet grass, check lined. The scattered irrigated sections of the western portion of the United States to which these grasses are adapted in their respective temperature regions are not indicated.

for orchard grass than has been indicated for timothy. Nevertheless, orchard grass can be grown to advantage in the Pacific Northwest on lands too dry to produce timothy profitably.

Orchard grass is used for hay and pasture. It is not as specific in its soil requirements as timothy. Helm (3) points out that it, like timothy, is best adapted to fertile loam soils, but orchard grass will grow also on poorly drained wet land, and on land that is poor and dry. Orchard grass, however, does not do well on very sandy soils. It is valued for its early growth in spring and late growth in autumn.

Tall Meadow Oat Grass (*Arrhenatherum elatius*). Tall meadow oat grass has the same climatic adaptation as orchard grass and is

used in the same area. It is a relatively short-lived perennial. Unlike orchard grass, tall meadow oat demands open soils and good drainage; it is especially adapted to light sandy and even gravelly soils. Tall meadow oat like orchard grass can be used to advantage in the irrigated areas of the western states. The regions in the United States to which orchard grass and tall meadow oat grass are best adapted are shown in Fig. 102.

Meadow Fescue (*Festuca elatior*). Meadow fescue finds use primarily as a pasture grass but can also be used to advantage for the production of hay. It is grown in the same general area as timothy. The grass, however, is more tolerant of the high summer temperature than either timothy or Kentucky bluegrass. In irrigated areas in the western states both orchard grass and meadow fescue are superior to bluegrass in that their rates of growth are not checked as much by high summer temperature as those of the bluegrasses. Meadow fescue prefers rich, moist, or even wet soils; it will not succeed on sandy areas. It is short-lived on dry soils or under conditions of low summer rainfall.

The Ryegrasses (*Lolium spp.*). Two species of ryegrasses are used in the United States, the short-lived, usually annual, Italian ryegrass (*L. multiflorum*), and the perennial or English ryegrass (*L. perenne*). In addition, the commercially known common ryegrass, also designated as domestic, Oregon, and western ryegrass, consisting usually of mechanical and genetic mixtures of the above two species, is also grown. The ryegrasses are used for pasture, hay, and to some extent as lawn grasses.

As pointed out by Schoth and Hein (12), the ryegrasses are not winter-hardy. They are for that reason grown principally in the Pacific coast states west of the Sierra Nevada and Cascade Mountains and in the southern humid states. In the southern and also in the northern states, both species behave largely as winter annuals and as annuals. In the South, they do not withstand the high temperatures of the summer months and, if seeded too far to the north, they fail to survive severe winters. Klages (7) reports high yields for one year of both species from fall seedings in north-central Oklahoma; owing to their inability to withstand high temperatures and drought, they did not survive the summer following seeding.

The ryegrasses are highly valued in northwestern Europe, particularly in England, for their rapid development and fast recovery

after grazing or cutting. Their use, however, is confined largely to soils of high fertility. In western Oregon and Washington they exhibit a wide range of soil adaptability, being regarded there as wet-land grasses. The best yields are, however, obtained on fertile soils with good drainage.

The common ryegrasses should not be confused with the wild ryegrasses, species of *Elymus*, which are adapted to quite a different environment than *Lolium*. The wild ryes are hardy and drought-resistant, while the common rye grasses are nonhardy and moisture-loving.

Reed Canary Grass (*Phalaris arundinacea*). Reed canary grass is a native of the temperate regions of Europe, Asia, and North America. It is especially valued in low-lying areas subject to overflow. According to Schoth (11), it does best in moist, cool climates, and ceases to be of much importance in areas where average mean minimum temperatures in winter are above 45°, or average mean maximum temperatures in summer are above 80°F. While the grass is especially adapted to moist and even swampy soils, selections of reed canary are being used to advantage on high, well-drained, productive soils if supplied with ample moisture for spring and early summer growth. Strecker (13) reports the production of reed canary on dry, sandy soils in Germany.

Figure 103, adopted from Piper (9), shows the regions of the United States to which reed canary grass is adapted. While the whole northern portion of the country is included in the area to which the grass is adapted, it can be grown in the drier western portions of the country only in the favored, moist areas or with the aid of irrigation.

GRASSES OF COOL, DRY REGIONS

Smooth Brome (*Bromus inermis*). Smooth Brome is a long-lived, hardy, perennial grass indigenous to a large part of Europe and Asia. Its chief merit lies in its drought resistance. In Europe it is used extensively on the Hungarian plains. In the United States and Canada it is the most important cultivated grass in the central and northern Great Plains area and in the Prairie provinces to the north. It is considered of value not only on relatively dry lands but also as a pasture grass in the irrigated valleys of the intermountain and Pacific Northwest states. The drought resistance of smooth

brome and its ability to grow on relatively poor, sandy, and even gravelly soils have attracted attention to this grass in humid areas. The grass has in recent years been used to some extent in pasture and meadow mixtures in the Hay and Pasture Region. It is, however, primarily a grass of the high plains of northern regions. While smooth brome is able to withstand moderate summer temperatures, it is decidedly adverse to a combination of high summer temperatures and high humidity. This accounts for its inability to

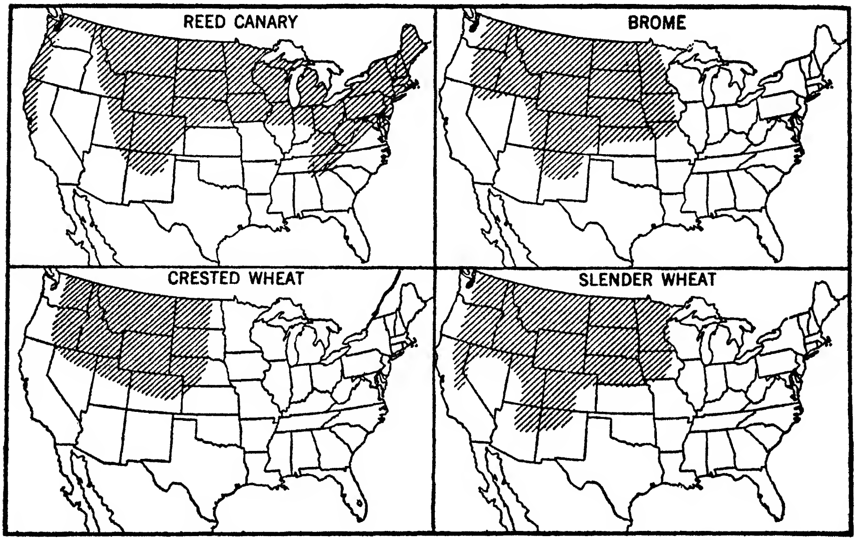


Fig. 103. Regions of adaptation of reed canary grass, upper left; smooth brome grass, upper right; crested wheat grass, lower left; and slender wheat grass, lower right. (Compiled from Piper, 9.)

invade the southern part of the Corn Belt. The region of the United States in which smooth brome grass is most valuable is shown in Fig. 103.

The Wheat Grasses (*Agropyron spp.*). Numerous species of *Agropyron*, both native to this country and of foreign extraction, have been found to be of value in dry areas. The one most extensively grown in the drier portions of the northwestern quarter of the United States is crested wheat grass (*A. cristatum*). This introduction from the northern regions of the U.S.S.R. has been extensively employed in reseedings of abandoned crop lands, and depleted ranges in the northern Great Plains and intermountain regions. It is well adapted for these purposes on account of its resistance to

extreme drought and cold, and on account of its excellent seed habits. The drought resistance of crested wheat grass, occasioned by its extensive root system, makes it of special value in dry-land agriculture in that its introduction has given to these areas a grass that can be incorporated to advantage into their rotation systems. High summer temperatures set a southern limit to its distribution. The regions of the United States to which crested wheat grass is most valuable are shown in Fig. 103. Crested wheat is used primarily as a pasture and range grass in areas too dry for the successful growing of smooth brome. The forage produced by crested wheat grass is rather harsh to produce the best type of hay. Dwarf growing, fine-leaved strains also have merits as lawn grasses in dry regions.

Slender wheat grass (*A. pauciflorum*) is a native of this continent. It has much the same growth habits as crested wheat, but lacks its extreme resistance to drought. Figure 103 shows that slender wheat is utilized farther to the east than crested wheat grass. In its western region of distribution it is used in moister localities than the crested wheat grass. In its native state it is most abundant on alluvial lands along streams and is found only occasionally on the higher and dryer bench lands. It does not withstand flooding. According to Piper (9), slender wheat "is notable for its ability to grow in alkali lands where most other grasses fail." The grass is used for pasture and for production of hay either where it occurs in native stands or where it has been seeded. Slender wheat grass was first cultivated around 1895, and is now grown most abundantly in Manitoba, Alberta, Saskatchewan, and the Dakotas. It is not, however, of as great importance as a cultivated grass in this area as smooth brome.

Western wheat grass (*A. smithii*) is another native of this hemisphere. According to Hoover (5), it is quite generally distributed throughout the United States, except in the more humid southeastern area, but is more at home in the northern Great Plains. It is a component of many native grassland meadows, and is also not uncommon in pure stands, especially on heavy gumbo soils of old lake beds. It is of interest to compare the root systems of the three wheat grasses mentioned. Crested wheat is a bunch grass; slender wheat is generally regarded as a bunch grass, but it will under favorable conditions produce short rootstocks; western wheat grass, on the other hand, has strongly creeping rootstocks and pro-

duces a tough sod. Like slender wheat, western wheat grass also lacks the extreme drought resistance of crested wheat.

The list of valuable wheat grasses is by no means exhausted by the above brief discussion. Before leaving this valuable group of grasses two native species of great importance to the drier areas of the Pacific Northwest must at least be mentioned. These are the bluebunch wheat grass (*A. spicatum*) and the beardless bluebunch wheat grass (*A. inerme*). They are used not only as range grasses in their native habitats but have in recent years been employed as cultivated grasses. Selections of these grasses equal crested wheat in drought resistance.

Other Native Species for Dry Areas. The list of valuable native species of grasses is so long that it will be impossible even to enumerate them here. Some of the more important ones must, however, be mentioned. Thus in the Great Plains area are found, just to name a few, the buffalo grass (*Buchloë dactyloides*); the bluestem grasses, big bluestem (*Andropogon furcatus*) and little bluestem (*A. scoparius*); the grama grasses, blue grama (*Bouteloua gracilis*) and side oat grama (*B. curtipendula*); switch grass (*Panicum virgatum*) and needle grass (*Stipa comata*), which also extends into the intermountain area. In the southwest area additional gramas are of importance, such as black grama (*Bouteloua eriopoda*); rothrock grama (*B. rothrockii*); and hairy grama (*B. hirsuta*), which also extends into the northern Great Plains in its minor distribution; tobosa grass (*Hilaria mutica*); curly mesquite (*H. belangeri*); galleta grass (*H. jamesii*); and vine mesquite (*Panicum obtusum*). Other native species of special importance in the Pacific Northwest besides those indicated in the brief discussion of the *Poas* and *Agropyrons* are the wild-rye grasses such as Canada wild-rye (*Elymus canadensis*); beardless wild-rye (*E. triticoides*); and blue wild-rye (*E. glaucus*).

WILD OR PRAIRIE HAY

Characteristics of Prairie Hay. The hay trade's conception of wild or prairie hay is that it consists principally of the bluestems (*Andropogons*), wheat grasses (*Agropyrons*), and slough grass (*Spartina michauxiana*) that grow either in practically pure stands or in mixtures with other grasses or miscellaneous forbs, on the virgin meadows of the Prairie and Great Plains states. These grasses ordinarily do not develop seed heads prior to cutting, and the hay therefore

does not have many distinct stems like that produced from the cultivated grasses. The exact species represented in the production of prairie hay are determined by the environmental conditions under which they are grown. It will be recalled from the discussion relating to the distribution of the grassland climates in the central area of the United States, Chapter XX, that the humid eastern portion of this great area is clothed with tall, the central portion with mixed, and the dry western expanses with short grass covers. This is primarily a response to the moisture factor of the environment. Keim *et al.* (6) bring out that even within confined limits, such as in an area comprising four counties in north-central Nebraska, rainfall and subirrigation play an important rôle in determining the yields and structures of the native vegetations of grasslands. Keim *et al.* present data showing the especially intricate relationship existing between the depth of the ground-water level and botanical structure. The most important differences in the botanical composition and relative degree of coarseness of the three commercial classes of prairie hay as recognized by the United States official standards are traceable to variations in moisture conditions existing on the upland and bottomland wild hay meadows. The three classes are upland prairie, upland-midland prairie mixed, and midland prairie. The first is characterized by an abundance of short leaves, few distinct stems, and by the fact that the hay is relatively soft to the touch. Midland prairie hay is made up of long, stringy, harsh leaves. Upland-midland mixed prairie hay consists of a mixture of upland and midland (bottomland) grasses. Since prairie hay is produced over a wide range of climatic and soil conditions, a great variation in its botanical composition is to be expected.

In the central and western areas of prairie hay production these hays are made up almost entirely of native plants. In the more humid eastern portion of the prairie hay producing region some of the native grasslands have, however, been invaded by certain cultivated species, such as timothy, redtop, the bluegrasses, and smooth brome.

Distribution of Prairie Hay Production. The distribution of wild grasses cut for hay in the United States is shown in Fig. 104, taken from Baker and Genung (2). Prairie hay production is of special importance in the Spring Wheat Belt; in Nebraska, and

especially in the Sand Hills section of Nebraska; in eastern Kansas; and in northeastern Oklahoma. The demand for land suitable for cereal production has materially decreased the area devoted to prairie hay in the past 30 years. To the east of the Great Plains, prairie hay production has disappeared almost entirely. The acreage shown in Wisconsin consists mostly of marsh hay. East of the Great Plains native grasslands have been forced into the production of corn and small grains; furthermore, the more favorable moisture relationships in this area make other forage crops such as the clovers,

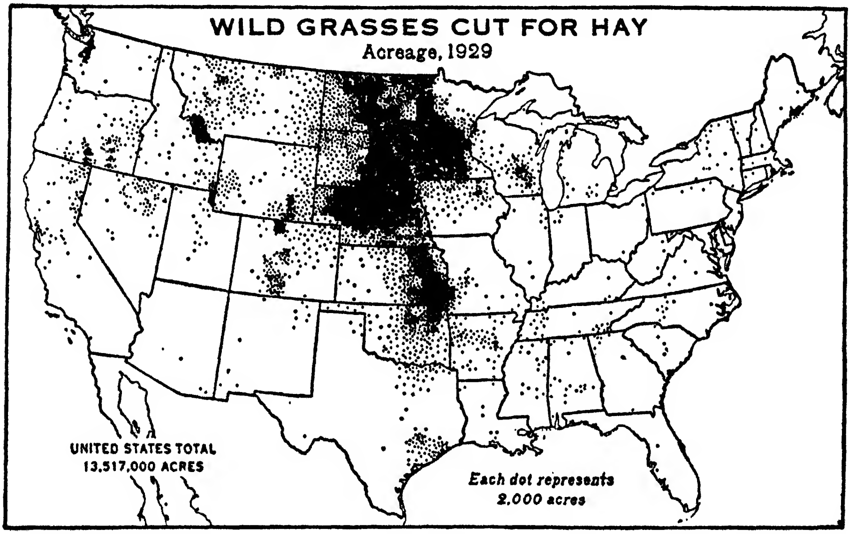


FIG. 104. Distribution of wild or prairie hay in the United States. Each dot represents 2,000 acres. (After Baker and Genung.)

alfalfa, and cultivated grasses more productive than native grasses. Another factor entering into the situation is that native grasslands cannot be incorporated into systems of crop rotations like cultivated legumes and grasses. In the Great Plains prairie hay continues to provide important supplies of feed. To the west of this area the climate is so dry that native grasses do not usually grow tall enough to be cut for hay except in the high mountain valleys.

GRASSES OF WARM, HUMID REGIONS

Bermuda Grass (*Cynodon dactylon*). Bermuda is the most important pasture and lawn grass of the more humid portions of the Cotton Belt, where it is relatively as important as Kentucky blue-

grass is in the North. The grass is a native of India, and of probably other tropical areas of the Old World. It was introduced into the United States during the early part of the eighteenth century and spread rapidly. The points of merit of this grass responsible for its extensive use are: its ability to make rapid growth under high temperature conditions; its adaptation to a great variety of soil conditions; its ability to withstand close grazing or close clipping; its aggressiveness; its value as a soil binder in erosion control; and its rather moderate demands for moisture. In addition to these points the grass is readily established by vegetative means, planting of sod pieces. It may also be established from seed. While the grass has a wide range in its soil adaptation, it does best on moist bottom lands. It grows luxuriantly enough to be utilized for hay only on the better soils in the central and southern area of its distribution. Furthermore, soils used for bermuda must be well drained. The grass is not without certain definite demerits. It will grow only under conditions of relatively high temperatures; for that reason it starts growth late in spring and enters into dormancy with the first drop of temperature in fall. The period over which it provides pasturage is therefore relatively short in relation to the length of the thermal growing season. In its northern area of distribution its growth is not sufficient to make the grass valuable, but there it becomes a rather troublesome weed and under some conditions may be difficult to eradicate.

The bermuda and carpet grass producing areas of the United States are indicated in Fig. 102. It will be observed that the range of distribution of bermuda coincides quite well with the distribution of cotton, except that owing to moisture limitations it does not extend as far to the west as cotton. It is also utilized in the irrigated areas of the southwest. The grass is grown in certain areas north of the line indicated in Fig. 102. Its value in such areas, however, is questionable on account of temperature limitations.

Carpet Grass (*Axonophus compressus*). Carpet grass, also known as Louisiana grass, being more exacting in its temperature and moisture demands than bermuda, is not as widely distributed. This is evident from Fig. 102. Its distribution extends neither as far to the north nor as far to the west as that of bermuda. Carpet grass is, according to Piper (10), especially adapted to sandy or sandy loam soils, particularly in places where moisture is near the

surface most of the year. On such areas carpet grass is more valuable than any other perennial grass for permanent pastures. Since carpet grass is less susceptible than bermuda to temperature depressions in autumn, it can be utilized for grazing over a longer period of the year than bermuda.

Johnson Grass (*Sorghum halepense*). Johnson grass is generally regarded more as a weed than as a forage grass. It is difficult to eradicate. Large areas of fertile land, particularly river bottoms, are infested with this grass. On such areas it is utilized to advantage for the production of hay and pasturage. Johnson grass occurs more or less in all of the Cotton Belt, except in the drier western portions. In the northern areas of the Cotton Belt it is killed out by occasional severe winters.

Johnson grass is frequently grown in combination with other crops such as winter oats or vetch. In such cases the infested areas are often plowed and seeded to winter annuals. Since such treatment relieves the sodbound condition of the Johnson grass, it stimulates rather than injures the grass.

Other Southern Grasses. A great variety of grasses of tropical origin can be used in the very southern portion of the United States. Space does not permit the discussion of these grasses in detail. Dallis grass (*Paspalum dilatatum*), a native of Argentina, is utilized from North Carolina to Florida and west to Texas. Klages found it exceedingly drought-resistant in north-central Oklahoma but unable to survive winter temperatures. Vasey grass (*Paspalum urvillei*), also a native of Argentina, is a close relative of Dallis grass and adapted to the same area in the United States. Guinea grass (*Panicum maximum*), a native of Africa, is adapted only to the very southern portion of the United States. Bahia grass (*Panicum notatum*), a native of Cuba and Mexico, is grown in the same region as Guinea grass. Natal grass (*Tricholaena rosea*) was after its introduction into the United States first grown as an ornamental. It has merits as a forage grass in Florida, along the Gulf coast, and in the very southern portion of California.

REFERENCES

1. Armstrong, S. F., *British Grasses and Their Employment in Agriculture*. University Press, Cambridge, England, 1937.

2. Baker, O. E., and A. B. Genung, "A graphic summary of farm crops," *U. S. Dept. Agr. Misc. Pub.* 267, 1938.
3. Helm, C. A., "Orchard grass in Missouri," *Mo. Agr. Exp. Sta. Circ.* 172, 1934.
4. Hitchcock, A. S., "Manual of grasses of the United States," *U. S. Dept. Agr. Misc. Pub.* 200, 1935.
5. Hoover, M. M., "Native and adapted grasses for conservation of soil and moisture in the Great Plains and Western States," *U. S. Dept. Agr. Farmers' Bull.* 1812, 1939.
6. Keim, F. D., A. L. Frolik, and G. W. Beadle, "Studies of prairie hay in north-central Nebraska," *Nebr. Agr. Exp. Sta. Res. Bull.* 60, 1932.
7. Klages, K. H. W., "Comparative ranges of adaptation of species of cultivated grasses and legumes in Oklahoma," *Jour. Amer. Soc. Agron.*, 21:201–223 (1929).
8. Piper, C. V., "Important cultivated grasses," *U. S. Dept. Agr. Farmers' Bull.* 1254, 1934.
9. ———, "Cultivated grasses of secondary importance," *U. S. Dept. Agr. Farmers' Bull.* 1433, 1934.
10. ———, *Forage Plants and Their Culture.* Macmillan, New York, 1937.
11. Schoth, H. A., "Reed canary grass," *U. S. Dept. Agr. Farmers' Bull.* 1602, 1938.
12. ———, and M. A. Hein, "The ryegrasses," *U. S. Dept. Agr. Leaflet* 196, 1940.
13. Strecker, W., *Die Kultur der Wiesen, ihr Wert, ihre Verbesserung, Düngung und Pflege.* Paul Parey, Berlin, 1923.

Chapter XXXII

MISCELLANEOUS CROPS

TOBACCO

Historical. The position of tobacco is unique in that it represents one of the most recent additions to the list of crops of world importance. Tobacco is a native of America. Linton (13) designates it as one of the most important gifts from the New World to the Old. The antiquity of tobacco and its use on this continent are indicated by Linton in the following paragraph.

> "In spite of the attempts of various authors to prove its Old World origin there can be no doubt that it was introduced into both Europe and Africa from America. Most species of Nicotiana are native to the New World, and there are only a few species which are undoubtedly extra-American. The custom of smoking is also characteristic of America. It was thoroughly established throughout eastern North and South America at the time of the discovery; and the early explorers, from Columbus on, speak of it as a strange and novel practice which they often find hard to describe. It played an important part in many religious ceremonies, and the beliefs and observances connected with it are in themselves proof of the antiquity of its use."

At the time of the discovery of America, tobacco was in general use over the greater parts of North and South America. The Indians of Central and South America were mostly cigar and cigarette smokers. The Spaniards, coming in contact mostly with these inhabitants of the New World, adopted the methods of the Indians by using tobacco in the form of crudely constructed cigars and cigarettes. The Spaniards in turn became the promoters of the cigar in Europe; they were slow, however, in making their product known to the other nations of Europe. According to Laufer (12), the cigar spread in Europe only in the first part of the last century. The cigarette was not introduced into England until the Crimean Campaign of 1854–1856, when it was brought back by British officers who had learned this new method of using tobacco from

their French and Turkish allies. The British had long been pipe smokers. Unlike the Spaniards, the British, in their early expeditions to the New World, contacted mostly the pipe-smoking Indians of North America. They, in turn, took up the use of tobacco in this form and became the most active propagators of pipe smoking. As stated by Laufer, "English sailors and soldiers, students and merchants carried the pipe victoriously wherever they went." The English also soon gained a reputation for the making of good pipes, a reputation and distinction that they hold to this day.

The rapid spread of the use and the culture of tobacco to nearly all sections of the world was amazing. England, Portugal, and Spain received tobacco directly from America. During the period of rapid expansion of commerce following the discovery of the Americas they, in turn, carried the plant and its products over all the world.

Tobacco was first introduced into Spain as an ornamental, and was later valued for its alleged medicinal values. Tobacco was grown in Portugal in 1558. The plant was first brought and made known in England by Sir John Hawkins around 1565. Here, as in Spain, the plant was apparently grown as a curiosity for some time before it was actually used. The smoking of tobacco in pipes in all probability originated with sailors who returned from America. It fell to the lot of Sir Walter Raleigh to popularize tobacco in England. Tobacco culture began to spread in France from 1560. Thevet and Nicot are credited with the introduction of tobacco into France. It was after the latter, Jean Nicot, that the generic name of the plant, *Nicotiana*, was coined. The plant made its entrance into Italy in 1561 under the sponsorship of two churchmen, the Cardinal Santa Cruce, who brought it from Portugal, and by the papal nuncio and ambassador of Toscana at the court of France, Nicolo Tornabuoni. Laufer brings out that tobacco was cultivated during the sixteenth century in many parts of Germany, chiefly around Nuremberg, in Saxonia, Thuringia, Hessen, the Palatinate, and Mecklenburg. Tobacco was first introduced into Norway in 1632. Peter the Great of Russia (1689–1725) became an adept smoker during his sojourn in England. He followed the custom earlier established in other countries, namely, to introduce tobacco into his country, not only for the pleasure it would afford to smokers, but also for the sake of the revenue it would yield. Jean Nicot, for

instance, was highly praised for having increased the revenue of the French government by the introduction of tobacco into the kingdom.

The use and culture of tobacco spread rapidly, not only in Europe, but also in the other continents. It was introduced into Turkey around 1605, and about the same date into Japan and China. Even early travelers in Africa report the cultivation and the use of tobacco among the natives of that continent.

The early rapid dissemination of tobacco may be accounted for in part by the many and novel virtues credited to it, such as allaying hunger, dispelling fatigue, and a great variety of medicinal uses. It was for a time regarded as a potent and benevolent drug "for the cure of many maladies." William Barclay (Edinburgh, 1614), writes of tobacco as having "much heavenlie vertue in store" and describes America as "the countrie which God hath honoured and blessed with this happie and holie herbe."

There was, however, definite opposition to the use of tobacco. Thus, King James of England in 1604 in his famed *Counterblaste of Tobacco* refutes, in the physiological terminology of his time, the medicinal virtues of the drug, and the absurdities written in praise of its alleged healing powers. James, after a long tirade, describes the use of tobacco as "a custome lothsome to the eye, hatefull to the nose, harmfull to the braine, dangerous to the lungs, and in the blacke stinking fume thereof, neerest resembling the horrible Stigian smoke of the pit that is bottomelesse." James's choice of words in the condemnation of tobacco makes rather refreshing reading. "It is a great contempt of God's good gifts that the sweetness of man's breath, being a gift of God, should be willfully corrupted by this stinking smoke. Moreover, which is a great iniquitie, and against all humanitie, the husband shall be ashamed, to reduce thereby his delicate, wholesome, and cleane complexioned wife, to that extremitie, that either shee must also corrupt her sweete breath therewith, or else resolve to live in a perpetual stinking torment."

The early importations of tobacco into England were in all probability of *Nicotiana rustica*, a small-leaved variety with a high percentage content of nicotine. It was the species in common use among North American Indians. This fact may also account for the ire of King James in condemning the crop. *Nicotiana rustica*

is not now cultivated as a smoking tobacco, excepting in portions of India. Its primary use is for the production of nicotine. The broad-leaved, low-nicotine species *N. tabacum* was commonly grown by the Indians of the West Indies and of Mexico. It is the type that entered world trade through the commerce of the Spaniards and Portuguese traders. *Nicotiana tabacum* was not introduced into Virginia until about 1610, coming there from Trinidad.

In spite of James's counterblast and other attempts to limit its use, consumption increased rapidly. The early history of tobacco production in the United States is summarized by Garner *et al.* (7) in the following paragraph.

> "From the small beginning at Jamestown, the production of tobacco in Virginia and Maryland increased rapidly, for it was about the only commodity the colonists could produce to exchange for the many manufactured products they required from Europe. From the crop of 20,000 pounds in 1618 at Jamestown, exports in 1627, only 9 years later, had increased to 500,000 pounds. In fact, although the foreign market rapidly expanded, production increased at an even greater rate. The total exports from Maryland and Virginia were 1,500,000 pounds in 1639, but the value per pound had declined from nearly 55 cents in 1619 to about 6 cents. At the outbreak of the Revolutionary War, exports of tobacco had increased to about 100,000,000 pounds, nearly all of which was produced in Virginia and Maryland. After the close of the Revolution, culture was extended into North Carolina, Kentucky, Tennessee, Ohio, and Missouri, and later to several other States. Domestic manufacture of tobacco first assumed importance after the Revolution and has continued progressively to absorb an increasing portion of the crop, until at present more than half of the total production is utilized for this purpose."

Utilization of Tobacco. Hill (9) discusses tobacco under the novel heading of "Fumitories and Masticatories." These two terms are well chosen to designate the utilization of tobacco. The leaf is either smoked in a pipe, in the form of cigarettes or cigars, or is "masticated" in the form of chewing tobacco or snuff. All of these uses are old. There is some difference of opinion as to whether the natives of the Americas chewed tobacco; however, the taking of the leaf in the form of snuff is a European innovation.

The relative use of tobacco in different forms has undergone change. This is evident from the per capita consumption of tobacco in various forms in the United States, expressed in pounds at five-year intervals, 1900–1935, Table 61 (2). The most spectacular

phase of the tobacco industry has been the amazing increase in cigarette consumption. As late as 1880, only a few cigarettes were made in the United States. In 1894, the Egyptian cigarette appeared and slowly made headway even though it was expensive. Soon American manufacturers began to add Turkish tobacco to improve the burning qualities of their product. In 1900, the per capita consumption of small cigarettes was only 34.9, by 1910 it was 93.7, by 1920, it was 418.8, ten years later 972.0, and in 1935 it amounted to 1,055.6. The production of small cigarettes in the United States increased from 532,719,000 in 1890; 3,254,131,000 in 1900; 47,430,105,000 in 1920; 123,802,186,000 in 1930 to 164,476,300,000 in 1938 (2 and 3). The cigarette came into great demand during the first World War and has consistently gained in popularity since that time.

TABLE 61. PER CAPITA CONSUMPTION OF TOBACCO PRODUCTS IN THE UNITED STATES AT FIVE-YEAR INTERVALS, 1900–1935, EXPRESSED IN POUNDS OF VARIOUS FORMS OF CONSUMPTION

Year	*Forms of Consumption*					*Total*
	Cigars *	Cigarettes *	Chewing Tobacco	Smoking Tobacco	Snuff	
1900	1.33	0.14	2.39	1.31	0.20	5.37
1905	1.59	0.15	2.09	1.92	0.25	6.00
1910	1.59	0.34	2.17	2.30	0.34	6.74
1915	1.58	0.67	1.77	2.36	0.33	6.71
1920	1.87	1.56	1.43	1.98	0.34	7.18
1925	1.39	2.07	1.10	2.14	0.33	7.03
1930	1.17	2.73	0.80	1.87	0.33	6.90
1935	0.97	3.04	0.55	1.84	0.28	6.68

* Pounds of cigars and cigarettes represent unstemmed equivalent of tobacco used in the manufacture of these products.

Nicotine is another product of tobacco of considerable value, being used extensively as an insecticide. The present supply is obtained almost exclusively from the by-products of the tobacco industry, that is, from the stems, waste, and low-grade leaves. The nicotine content of the commonly used *Nicotiana tabacum* is relatively low. *Nicotiana rustica*, on the other hand, has a high percentage content of nicotine. Under favorable conditions, *N. rustica* has produced yields of 150 pounds of nicotine per acre.

The United States is by far the most important exporting country, exporting for the five-year period 1930–1934 in excess of 479 million pounds annually. Other important exporting countries, with their exports stated in rounded figures of millions of pounds for the same period, are: Netherland India, 144; Greece, 88; Brazil, 67; Turkey, 67; Bulgaria, 49; the Philippine Islands, 45; Cuba, 38; British India, 36; Algeria, 26; and Hungary, 23. The countries of northwestern Europe are the outstanding importers of the commodity.

It will be impossible to discuss here the conditions under which tobacco is grown in its many areas of production. The areas producing tobacco of exceptional quality must, however, at least be mentioned. The quality of American tobacco varies in the different areas of production but is generally good and under normal conditions enjoys a good export demand. Cuba produces cigar tobaccos of exceptional quality. Sumatra and Java produce a fine light tobacco particularly useful for cigar wrappers. Turkey and Greece produce a high type of cigarette tobacco which is extensively used for blending purposes. According to Lippincott (14), American companies buy 65 to 70 per cent of the output of the Smyrna and Samsun districts of Asia Minor. Two other important producing areas in Asia Minor and the Levant are the Trebizond and Latakia districts. According to Finch and Baker, "Samsun and Smyrna tobaccos are strong and highly aromatic; Trebizond tobacco is light and mild; while Latakia is artificially flavored with certain herbs in the process of curing." The Xanthé, Kavalla, and Salonika areas of Greece produce cigarette tobaccos of quality. The leaf produced in these areas of Asia Minor and Macedonia bears, according to Finch and Baker, the same relation to the cigarette industry that Cuban tobacco bears to the cigar industry.

Distribution in the United States. The production of tobacco in the United States is highly localized. This holds true not only for the crop as a whole but especially for the production of each principal type of leaf demanded by the increasing specialization in tobacco manufacturing. According to Hutcheson *et al.* (11), the tobacco crop of the United States occupies only 0.40 per cent of the total acreage in crops. Yet, in 1932 the crop ranked seventh in value of the crops grown in the country. In 1935 the value of the tobacco crop was exceeded only by the values of the corn,

all hay, wheat, cotton, and oats crops. The farm value of the tobacco crop for that season was estimated at $237,389,430, while the farm value of the potato crop dropped slightly below that figure, namely to $230,668,860.

Three main classes of tobacco are generally recognized: (*a*) cigar tobacco; (*b*) manufacturing tobacco; and (*c*) export tobacco. These classes are further divided into types according to special characteristics and appropriate use. The three principal types of cigar tobacco correspond to the three parts of the cigar, namely, wrapper leaf, binder leaf, and filler leaf. The principal commercial manufacturing and export types are the fire-cured, dark air-cured, flue-cured, the Maryland, and Burley. Manufacturing and export types of tobacco are used for cigarette, pipe-smoking, and chewing mixtures.

Table 63 gives the statistics of tobacco production in the United States by states for the ten-year period of 1928–1937 and the production for 1938. It will be observed that two states, North Carolina and Kentucky, account for almost 60 per cent of the production of the country. Six states produce in excess of 85 per cent of the total crop.

TABLE 63. TOBACCO: ACREAGE HARVESTED, YIELD PER ACRE, PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION

Rank	*States*	*Average Number of Acres Harvested 1928–1937*	*Yield, in Lbs.*	*Production*		
				Average 1928–1937, in 1,000 Lbs.	Percentage of U. S. Total	1938, in 1,000 Lbs.
1	North Carolina	645,830	766	493,927	36.31	517,210
2	Kentucky	411,820	780	321,370	23.62	289,115
3	Tennessee	129,770	838	108,818	8.00	98,687
4	Virginia	141,890	701	98,075	7.21	98,906
5	South Carolina	102,500	779	79,624	5.85	98,800
6	Georgia	79,080	816	66,787	4.91	90,950
7	Pennsylvania	31,050	1,228	37,923	2.79	32,110
8	Ohio	37,640	891	33,294	2.45	23,885
9	Wisconsin	24,910	1,316	32,098	2.36	32,710
10	Maryland	35,740	704	25,217	1.85	29,250
	Other states	60,030	1,054	63,267	4.65	64,200
	Total U. S.	1,700,260	803.2	1,360,400	100.00	1,375,823

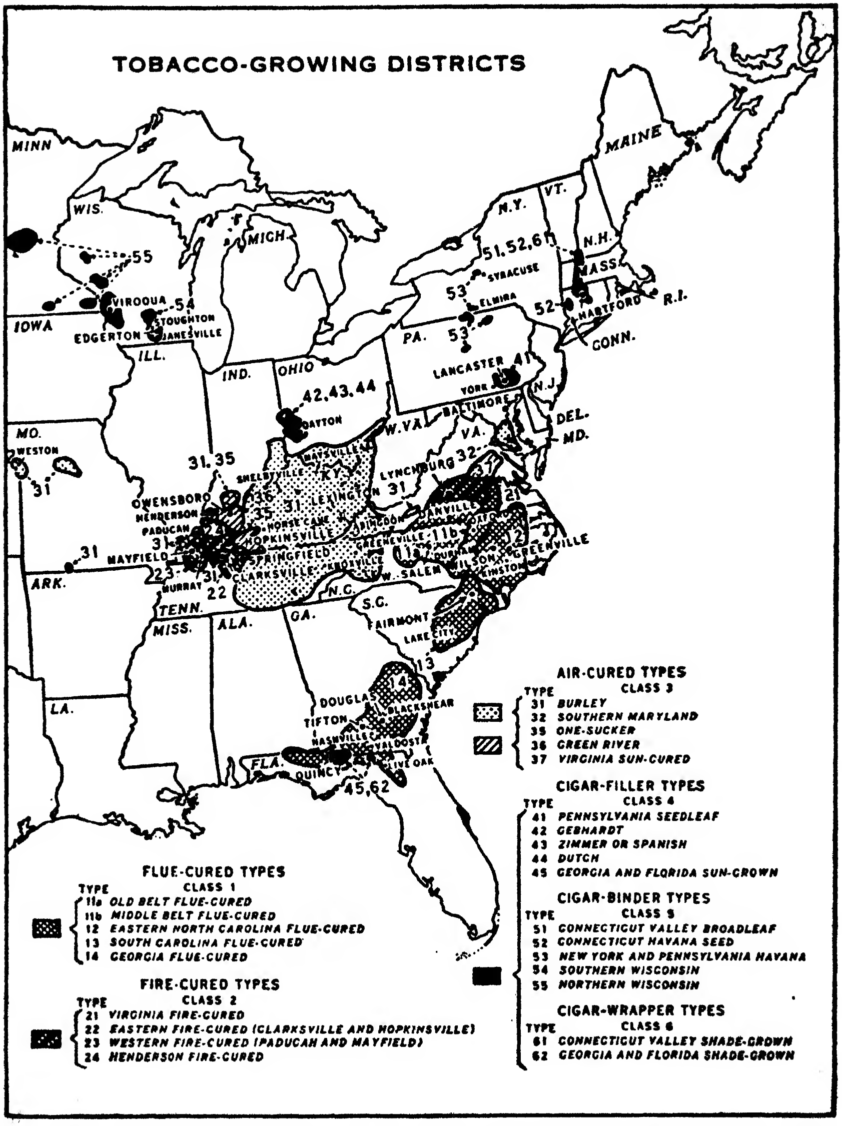


Fig. 106. Locations of the tobacco-growing districts of the United States. (After Morrow and Smith.)

Table 64, taken from Garner *et al.* (7), lists the principal commercial types of tobacco, indicates the areas in which they are grown, gives their chief uses, and shows the varieties used in their production. Figure 106, taken from Morrow and Smith (16),

TABLE 64. THE PRINCIPAL COMMERCIAL TYPES OF TOBACCO, AREAS IN WHICH THEY ARE GROWN, THEIR CHIEF USES, AND THE VARIETIES USED IN THEIR PRODUCTION IN THE UNITED STATES — (AFTER GARNER, ALLARD, AND CLAYTON)

Type of Leaf	*Area in Which Mainly Grown*	*Chief Use*	*Variety of Seed*
Fire-cured (U. S. types 21–24)	Central Virginia, western Kentucky, and northwestern Tennessee	For export, manufacture of snuff and plug wrappers	Orinoco
Dark air-cured (U. S. types 35, 36, 37)	Immediately east of fire-cured area of Kentucky and Tennessee, and in north-central Virginia	For chewing plug and export	Orinoco, One Sucker
Maryland (U. S. type 32)	Southern Maryland	For cigarettes and export	Maryland Broadleaf
Cigar wrapper, shade-grown (U. S. types 61, 62)	Connecticut Valley and Quincy, Florida	Cigar wrapper	Cuban, Florida 301, Round Tip
Cigar binder (U. S. types 51, 52, 54, 55)	Connecticut Valley, southern and southwestern Wisconsin	Cigar binder	Connecticut Broadleaf, Havana seed
Cigar filler (U. S. types 41, 44)	Lancaster, Pa., and southwestern Ohio	Cigar filler	Pennsylvania Seedleaf, Ohio Seedleaf, Zimmer Spanish, Little Dutch
Flue-cured (U. S. types 11, 14)	Southern Virginia, northern and eastern North Carolina, eastern South Carolina, southern Georgia, northern Florida	Cigarettes, pipe and chewing tobaccos, and for export	Orinoco
Burley (U. S. type 31)	Central and northern Kentucky, southeastern Indiana, southern Ohio, western West Virginia, eastern and central Tennessee, western North Carolina, western Virginia	Cigarettes, pipe and chewing tobaccos	White Burley

shows the tobacco producing districts of the United States together with the types produced in each district. Baker and Genung (1) give the distribution of the tobacco acreage in the United States.

The United States is the world's greatest exporter of tobacco. But the country is also an importer of quality leaf. Cigar leaf is imported from Cuba and Puerto Rico, wrapper leaf from Sumatra and the East Indies, and Turkish cigarette tobaccos from Asia Minor and Greece. However, exports far exceed imports. In 1934 the United States exported 440,866,000 pounds of leaf and imported 57,786,000 pounds.

The United States is also a great consumer of tobacco, being surpassed in per capita consumption only by the Netherlands. The per capita consumption of all tobacco products in various countries for 1932 were as follows: Netherlands, 7.80 pounds; the United States, 6.00 pounds; Belgium, 5.49 pounds; Denmark, 4.43 pounds; United Kingdom, 3.32 pounds; Germany, 3.24 pounds; Sweden, 2.98 pounds; and France, 2.90 pounds.

Hill makes an interesting observation regarding the import demands of various nations. "England, a great pipe-smoking country, demands the best and strongest grades. Germany prefers a thick leaf, rich in oil and reddish in color. Switzerland demands the best quality, Italy and Austria a good grade, while France and Spain are satisfied with the poorer grades."

HOPS

(*Humulus lupulus*)

Historical. Nothing is known concerning the date at which the hop plant was first brought under cultivation. The hop was known to the early Greeks, even if only in its wild stage. It is described by Pliny in his *Natural History* as *lupulus*, *lupulus salictarius*, an appetizer and salad.

Gross (8) discusses the earliest report of the hop as a cultivated plant in the following paragraph.

> "The earliest reports on the hop as a cultivated plant date from the Carlovingian epoch, King Pepin le Bref having donated homularias (hop gardens) to the monastery of St. Denis about the year 768. As it would be straining a point to assume that hops would be extensively grown for any other purpose at that period, it may be reasonably supposed that they were used as an aromatic for the malt liquor cerevisia

then in general repute. Weaker malt beverages biera, canum and oel were also manufactured."

During the Middle Ages, hop gardens were cultivated to a limited extent as adjuncts to monasteries in central Europe. Hops are mentioned in connection with the Freising monastery around the year 850. However, hopped beer apparently did not become general in Germany until the fourteenth century. The crop became of importance in Flanders during the fourteenth century. Hops were introduced into England toward the close of the fifteenth century. Henry VII and Henry VIII prohibited their use in beer. Edward VI, however, formed a better opinion of hops, and granted numerous privileges in connection with their cultivation. Hops have been grown in central Europe for centuries. Bohemia soon gained a reputation for the production of hops of high quality, a distinction that this area has held up to the present time.

According to Smith (18), hop growing in North America began in New Netherlands as early as 1629 and in Virginia in 1648, although it did not become important until about 1800. In 1849 the New England states and New York produced nearly 1,500,000 pounds, of which New York produced 70 per cent. After the Civil War the industry developed in Wisconsin. In 1879 the state of New York produced an all-time maximum crop of 21,629,000 pounds. The growing of hops on the Pacific coast was started between 1858 and 1869. Production there increased gradually until at the present time the production of the crop in the eastern areas is negligible. The harvested hop acreage in the United States declined from more than 40,000 to less than 20,000 acres during the period of national prohibition. Since the legalization of beer in 1933, there has been a general increase in acreage and even a revival of hop production in the state of New York.

Utilization. Hops are grown for the production of lupulin, consisting of resins and essential oil, which imparts the characteristic flavor to beer, ale, and other malt beverages. The essential oil also contributes to the aroma and keeping qualities of beer and ale. Furthermore, the tannins occurring in the scales (or bracts) and stems of the cone of the hop aid in the clarification of the brew after boiling. The amount of hops required in the brewing industry is rather small. Each 31-gallon barrel of beer brewed in the United States requires only $\frac{1}{2}$ to $\frac{4}{5}$ pound of hops, though in some countries

beer is more heavily hopped so that the figures sometimes reach $1\frac{1}{4}$ pounds.

Climatic and Soil Relationships. The hop plant is somewhat similar to tobacco in that the quality of the product is rather markedly influenced by environmental factors. The hop is a plant of the central temperate zone. It does best under temperature conditions without sharp and often repeated fluctuations. According to Gross, the plant develops more satisfactorily when the temperature rises slowly and constantly from early spring up to the middle of summer, and then gradually and uniformly recedes. The hop plant demands a fairly abundant supply of moisture. Ideal moisture conditions are provided where the plant has an abundant supply accumulated during the winter months to draw upon. After growth starts, cold spring rains are harmful. An abundance of moisture is desirable during late spring and during early summer, that is, during the period of rapid growth. The latter part of the summer should be dry. Excessive moisture in late August and in September frequently leads to severe losses from various fungus diseases and plant lice.

The hop plant is a long-lived perennial. Long severe winters frequently result in the killing out of many of the plants. This offers another reason for the location of the crop in rather moderate areas.

Being a deep-rooted plant, the hop requires a deep, well-drained soil. Alluvial soils, or deep sandy or gravelly loam soils, are most desirable. Heavy clay soils, especially if wet, must be avoided.

Distribution. Table 65 gives the world statistics on hop production for the five-year period 1930–31 to 1934–35. Data on production in the Union of Soviet Socialist Republics are not available. It is known, however, that the crop is of some importance in Russia. It will be observed that only two non-European areas — the United States, Australia, and New Zealand — produce hops extensively. The crop is of special importance in Germany. Most of the production there is found in the southern part of that country, in Bavaria, Württemberg, and in Bohemia, that is, in areas where rather moderate climates prevail. England and Wales have long been important hop producers; again, the climate is moderate.

TABLE 65. WORLD STATISTICS ON HOP PRODUCTION FOR THE FIVE-YEAR PERIOD 1930–31 TO 1934–35

Rank	Country	Acreage in Acres	Production: In 1,000 Lbs.	Production: In Percentage of World Total *
1	Germany	56,060	37,584	34.23
2	United States	26,000	31,566	28.75
3	England and Wales	18,198	24,304	22.13
4	France	5,351	3,637	3.31
5	Poland	6,198	3,450	3.14
6	Yugoslavia	5,291	3,116	2.84
7	Australia and New Zealand	1,546	2,688	2.45
8	Belgium	1,931	2,009	1.83
	All others *	1,433	1,459	1.32
	World total *	122,008	109,813	100.00

* Excluding the U.S.S.R.

The United States is an important producer and exporter of hops. According to Hoerner and Rabak (10), hops were at one time grown in many areas of the United States, but they have never been of commercial importance except in New York and on the Pacific coast.

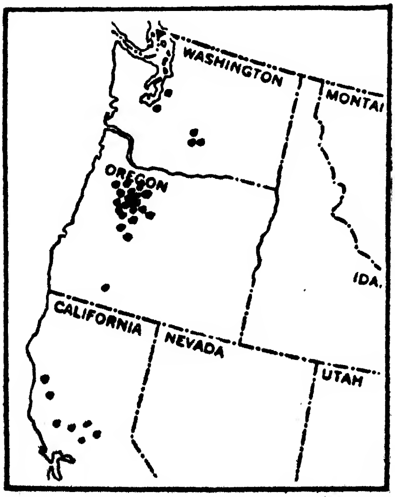


FIG. 107. Hop production in the United States in 1938. Each dot represents 1,000 acres. Nearly the entire crop is produced on the Pacific Coast.

Powdery mildew and prohibition practically eliminated the crop from New York until very recent years, when the industry revived in the western and central portions of the state. Nearly the entire crop is produced on the Pacific coast. For the ten-year period of 1928–1937 Oregon produced 18,352,000 pounds or nearly 51 per cent of the country's total crop. California produced 8,695,000 and Washington 7,032,000 pounds. Figure 107 shows the distribution of the hop acreage in 1938. The importance of the Willamette Valley of western Oregon is evident.

BUCKWHEAT

(*Fagopyrum spp.*)

Importance of the Crop. Buckwheat, except in limited regions, is a crop of minor importance both in world agriculture and in the United States. Quisenberry and Taylor (17) bring out that for every bushel of buckwheat grown in the United States there are produced about 300 bushels of corn, 100 bushels of wheat, 150 bushels of oats, 35 bushels of barley, and 5 bushels of rye.

Buckwheat probably originated in the mountains of central and western China. It was brought to the United States from Europe by early colonists. Buckwheat cakes seem to have fallen off in favor since more and more heavy manual labor is performed by means of machinery. Around 1866, buckwheat was grown on nearly 800,000 acres; more than a million acres were grown in the United States in 1918. Since that time the crop has decreased in importance.

Three species of buckwheat are recognized: (*a*) common (*Fagopyrum esculentum*); (*b*) Tartary or Siberian (*F. tartaricum*); and (*c*) notch-seeded buckwheat (*F. emarginatum*). The three varieties of buckwheat—Japanese, Silverhull, and Common Gray—generally grown in the United States belong to the *F. esculentum* species. Tartary buckwheat is recommended for its superior hardiness. Zavitz (19) records high yields of this species in Ontario.

Outside of its main areas of production, buckwheat is frequently grown as a catch crop. Since it requires but a short period to complete its cycle of development, it fits well into a cropping program to replace a crop that may have been destroyed earlier in the season. Buckwheat is able to produce a crop in from 10 to 12 weeks. The crop also has merits as a honey plant and can be used to advantage for soil-improvement purposes.

Climatic and Soil Relationships. Buckwheat is a crop of moist, cool climates. It will grow at rather low temperatures. This, together with its short growing season, makes it a good crop at high latitudes and at high elevations. Buckwheat has a distinct critical period at flowering time. High temperatures and dry weather, and also hot weather with frequent rains at that time, are often disastrous to the crop. Such conditions lead to a poor set of seed, because of the blasting of the flowers. This makes buckwheat a

rather hazardous crop. Seeding is often delayed in spring so that the principal growth may take place during relatively warm portions of the year and seed formation during the cooler months of late summer and early autumn. In the western areas of its production in the United States the crop is often seeded early enough to bring it into bloom late in July, that is, before temperatures get too high.

Buckwheat is extremely tolerant of poor soil conditions. It will produce a better crop on infertile, acid, poorly tilled lands than any other grain if the climatic conditions are favorable. Like other crops, buckwheat responds to good treatment with increased yields. It is well adapted to light, well-drained soils such as sandy loams and silt loams. The crop will not do well on heavy, wet soils. High fertility is not required; as a matter of fact, the crop lodges rather readily on such soils. Buckwheat is ideally adapted to poor lands in that it can compete successfully there with other grain crops. Other crops are usually more profitable on fertile soils, except where buckwheat may be used as a catch crop.

Distribution. Among the countries of the world, the Soviet Union has the largest production of buckwheat, with France ranking second, Poland third, Canada fourth, and the United States fifth. Other producing countries are Japan, Germany, and Rumania.

TABLE 66. BUCKWHEAT: ACREAGE HARVESTED, YIELD PER ACRE, PRODUCTION — AVERAGES FOR THE TEN-YEAR PERIOD 1928–1937 — AND 1938 PRODUCTION. ACREAGE AND PRODUCTION EXPRESSED IN THOUSANDS

Rank	*States*	*Acreage Harvested*	*Yield, in Bu.*	*Production*		
				Average 1928–1937, in Bu.	Percentage of U. S. Total	1938, in Bu.
1	Pennsylvania	149	17.7	2,620	32.90	2,170
2	New York	152	17.1	2,586	32.47	2,496
3	Ohio	23	16.8	384	4.82	210
4	West Virginia	20	17.2	354	4.45	256
5	Minnesota	32	9.1	306	3.84	172
6	Michigan	22	11.7	264	3.31	243
7	Indiana	16	13.6	215	2.70	168
8	Maine	12	18.0	209	2.62	130
9	Wisconsin	17	11.0	187	2.35	150
10	Virginia	14	12.8	180	2.26	162
	Other states	51	12.9	659	8.28	497
	Total U. S.	508	15.8	7,964	100.00	6,654

Table 66 gives the buckwheat statistics for the United States by states, while Fig. 108 shows the distribution of the crop. New York and Pennsylvania produce in excess of 65 per cent of the crop. It will be observed from Fig. 108 that the crop is of greatest importance in south-central New York, northwestern and north-central Pennsylvania, in the western counties of Maryland, and in

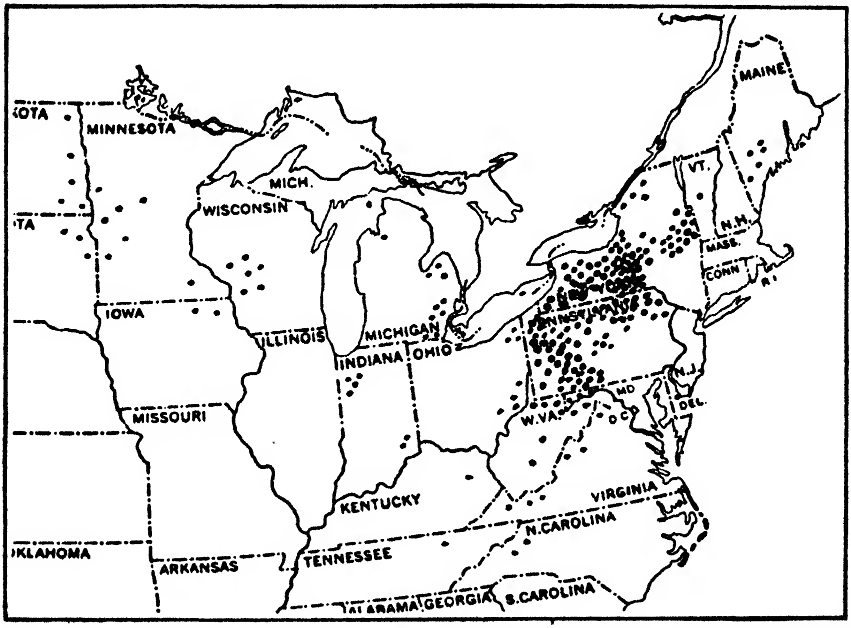


FIG. 108. Distribution of buckwheat in the United States in 1938. Each dot represents 2,000 acres.

north-central West Virginia. In general these areas of high production follow the higher and rougher topographies. Because of its inability to compete successfully with other crops, buckwheat is of little agricultural importance outside of these areas. Its use in other sections of the United States is confined to special purposes such as a honey crop, or catch crop. The growing of the crop for these special purposes accounts for the scattered appearance of buckwheat over much of the northeastern quarter of the United States.

REFERENCES

1. Baker, O. E., and A. B. Genung, "A graphic summary of farm crops," *U. S. Dept. Agr. Misc. Pub.* 267, 1938.

2. Bureau of Agricultural Economics, "First annual report on tobacco statistics," *U. S. Dept. Agr. Statistical Bull.* 58, 1937.
3. ———, "Annual report on tobacco statistics, 1938," *U. S. Dept. Agr. Statistical Bull.* 67, 1938.
4. ———, "World acreage and production of tobacco by countries," *U. S. Dept. Agr. Historical Series*, 1938.
5. Finch, V. C., and O. E. Baker, *Geography of the World's Agriculture.* Govt. Print. Office, Washington, D. C., 1917.
6. Garner, W. W., "Tobacco culture," *U. S. Dept. Agr. Farmers' Bull.* 571, 1936.
7. ———, H. A. Allard, and E. E. Clayton, "Superior germ plasm in tobacco," *U. S. Dept. Agr. Yearbook* 1936:785–830.
8. Gross, E., *Hops*, Trans. German by Charles Salter. Scott, Greenwood, London, 1900.
9. Hill, A. F., *Economic Botany.* McGraw-Hill, New York, 1937.
10. Hoerner, G. R., and F. Rabak, "Production of hops," *U. S. Dept. Agr. Farmers' Bull.* 1842, 1940.
11. Hutcheson, T. B., T. K. Wolfe, and M. S. Kipps, *The Production of Field Crops.* McGraw-Hill, New York, 1936.
12. Laufer, B., "Introduction of tobacco into Europe," *Field Museum of Natural History Anthropology Leaflet* 19, Chicago, 1924.
13. Linton, R., "Use of tobacco among North American Indians," *Field Museum of Natural History Anthropology Leaflet* 15, Chicago, 1924.
14. Lippincott, I., *Economic Resources and Industries of the World.* Appleton, New York, 1930.
15. Morgan, M. F., J. H. Gourley, and J. K. Ableiter, "The soil requirements of economic plants," *U. S. Dept. Agr. Yearbook* 1938:753–776.
16. Morrow, J. V., and D. Smith, "Tobacco shrinkage and losses in weight in handling and storage," *U. S. Dept. Agr. Circ.* 435, 1937.
17. Quisenberry, K. S., and J. W. Taylor, "Growing buckwheat," *U. S. Dept. Agr. Farmers' Bull.* 1835, 1939.
18. Smith, D. C., "Varietal improvement in hops," *U. S. Dept. Agr. Yearbook* 1937:1215–1241.
19. Zavitz, C. A., "Farm crops," *Ont. Agr. Col. Bull.* 228, 1915.

AUTHOR INDEX

SUBJECT INDEX